Development of selectivity systems for gadoid trawls

Tests with sorting grids, shortened lastridge ropes and vertical separation onboard R/V Helmer Hanssen

Scientific status report June 2021

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Abstract

The compulsory size selection system in the Barents Sea bottom trawl gadoid fishery comprises of a 55 mm bar spacing grid and a 130 mm mesh codend. The system stands before different challenges regarding maneuverability, reliability and performance and therefore, trials with different potential solutions and alternatives are carried out. The present status report summarizes the results at the time being for three cruises carried out onboard the research vessel Helmer Hanssen in the period December 2020 – March 2021. The cruises were conducted mainly in the southern Barents Sea and tested vertical separation of cod and haddock in the trawl entrance, codends with shortened lastridges, grids with different bar spacings, a new grid design from the Faeroe Islands and a 2- vs 4-panel Sort-V grid system.

The results showed that the vertical separation trawl, which was tested in two different configurations, did not work as expected and was not able to separate cod and haddock. Shortened lastridge codends, which were tested during two different cruises, demonstrated to significantly improve the size selection properties of standard diamond mesh codends and showed potential to selectivity properties similar to those obtained with sorting grids. As expected, tests with a 45 mm bar spacing steel grid resulted on reduced loss of commercial-sized fish. The tests with a new grid system design from the Faeroe Islands showed that although the concept of substituting the steel grid by a plastic grid in a Sort-V-like grid system is good, the design of the section resulted on an underperforming grid system. Finally, comparisons of the 2- and 4-panel configurations of the Sort-V grid system, revealed that the 4-panel configuration performs worse than the 2-panel configuration, and indicated that the differences in the lifting panel are not the only source for the difference in performance, and that the performance of grid sections is sensitive to moderate changes.

Further work to better understand the sorting mechanisms in sorting grids and alternative codend designs that can supplement or substitute sorting grids is recommended in the future.

Sammendrag

I henhold til dagens gjeldende regelverk er det i bunntrålfisket etter torsk i Barentshavet påbudt med sorteringsrist med 55 mm spileavstand, samt en sekk med 130 mm maskevidde. Dette systemet har vist seg å ha flere utfordringer, bl.a. utfordringer med håndtering samt stabil seleksjon. På bakgrunn av disse utfordringene har det blitt utført flere forsøk for å undersøke potensielle alternative løsninger. Denne statusrapporten summerer resultatene fra tre forsøk som ble utført ombord F/F «Helmer Hanssen» i perioden desember 2020 – mars 2021. Forsøkene ble utført i den sørlige delen av Barentshavet. Følgende alternativer ble testet; vertikal seperasjon av torsk og hyse i trålåpningen, sekk med innkortede leisetau, sorteringsrister med ulike spileavstander, en ny type sorteringsrist fra Færøyene, og to- vs. fire-panels Sort-V ristseksjoner.

Resultatene fra forsøkene viste at vertikalseparasjon av torsk og hyse, ved å sette inn et vertikalt delenett i trålbelgen som ledet til to sekker ikke fungerte. Trålpose med innkortede leisetau ble testet på to tokt og viste signifikant bedre seleksjon sammenlignet med en standard sekk. Seleksjonen i en sekk med innkortede leisetau viste seg å være på lik linje med seleksjonen i en sorteringsrist. Forsøkene med en sorteringsrist med 45 mm spileavstand viste som forventet redusert tap av fisk over minstemål. Forsøkene med en ny type rist fra Færøyene laget i plast viste forenklet håndtering, men ristene hadde betydelig dårligere seleksjonsegenskaper sammenlignet med standart Sort-V ristene i stål. Forsøkene der to- og fire-panels Sort-V rister ble sammenlignet viste at sistnevnte hadde dårligere seleksjon. Dette skyldtes til dels, men ikke utelukkende, ulike i løftepaneler og viser at seleksjonsegenskapene til påvirkes av små endringer.

Videre forsøk for å oppnå økt forståelse av seleksjonsprosessene i sorteringsrister, samt alternative design av trålposer som kan supplere eller erstatte sorteringsristene anbefales.

1. Background

The project “Development of selectivity systems for gadoid trawls” is a National initiative in Norway that aims at solving issues and challenges related to species and size selectivity in gadoid trawls. The main objective of the project is to:

- Contribute to improve exploitation patterns of cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and saithe (*Pollachius virens*) in the Norwegian Sea and Barents Sea bottom trawl fisheries by developing existing selection systems and introducing alternative solutions.

And this main objective will be fulfilled through the following secondary objectives:

- Develop and test new user-friendly grid designs that can substitute the grids used in the fishery today (i.e. Flexigrid).
- Test and document the properties (incl. selectivity properties) for different codend designs that would potentially substitute the grid+codend gear used in the fishery today.
- Study the effect of using different bar-spacings and meshes for the exploitation pattern of cod, haddock and saithe.

The project is led by the Institute of Marine Research in Norway in close cooperation with the Arctic University of Norway and SINTEF Ocean AS, which are the three leading institutes in Norway regarding fishing gear technology research. In addition to these three institutes the Federal Research Institute of Fisheries and Oceanography (PINRO) and the Directorate of fisheries in Norway will participate as partners in the project. The directorate of fisheries and the Norwegian Research and Aquaculture Research fund are the main financing organisms in the project.

The project started with a meeting in October 2021, where the leading research institutes, financing organisms and fishermen participated. The challenges in the fishery and plans for the project were reviewed according to the project description (Sistiaga et al., 2020) and the priorities for the cruises planned in winter/spring 2021 were discussed. The meeting participants brought up the following points:

- Fishermen lose up to 60-80% of commercial-sized haddock.
- In general, the fleet is little interested haddock under 44/45 cm because of its lower value.
- Species separation is of interest as periodically haddock is the target species.
- Earlier results with gear other than sorting grids (e.g. T90 codends) can provide results equivalent selectivity results.

Based the points discussed above, the following research was proposed:

- Test 4-panel square mesh codends and codends with shortened lastridges.
- Revise the possibility to use a vertically separated trawl to separate cod and haddock.
- Test a new sorting grid section designed in the Faeroe Islands.
- Test a flexigrid system with lower bar spacing in the second grid.
- Test different bar spacing grids and mesh sizes that can lead to higher retention of commercial-sized fish.

Based on the proposals received the project group carried out three cruises in the period December 2020 – March 2021 onboard the research vessel Helmer Hanssen, which belongs to the Arctic University of Norway. The sections below describe the equipment tested in each cruise and include a summary of the results obtained. The results from the cruises will be finally published in scientific journals and at the moment this status report was completed they have been analyzed to a different extent. Thus, the data presented here can be expected to be further analyzed and completed through the project period.

2. Cruise December 2020 onboard R/V Helmer Hanssen

2.1. Test of a Faeroese grid design and grids with different bar spacing

2.1.1. Introduction

Sorting grids used to supplement the size selectivity of diamond mesh codends in the Barents Sea were developed in Norway and Russia during the 90-s (Larsen and Isaksen, 1993) and have been compulsory since 1997. Fishermen can use three different sorting grid models i.e. Sort-X, Sort-V and Flexigrid, but only the latter two are used by the fleet today (Fig. 1).

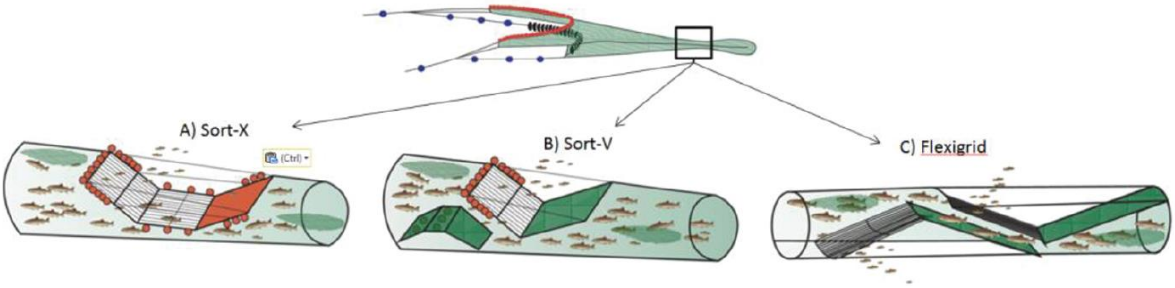


Figure 1: Mandatory sorting grids in the Barents Sea Demersal Fishery: (A) Sort-X, (B) Sort-V, and (C) Flexigrid.

The use of these two grids have different challenges and therefore alternatives to the existing grid designs are sought. The Sort-V grid is a steel grid and has the advantage that it is in principle not subjected to deformation due to tensions in the gear or continued use. However, it is heavy, rather large and implies challenges on deck specially on bad weather and when the space available is limited. On the other hand, the flexigrid is a grid system with two grids where the grids themselves are constructed of rubber and plastic and have neutral buoyancy i.e. there is no need for floats. Thus, the system is much lighter and easier to maneuver. Despite these advantages over the Sort-V system, the flexigrid has been reported to have the potential to change its structure and form with use and retain substantially more undersized fish than allowed by the regulations (Sistiaga et al., 2016; Brinkhof et al., 2020). Therefore, and considering the different challenges experience by both legal grids, a new grid design that is lighter, more maneuverable and with stable size sorting properties is sought.

The compulsory size selection system in the Barents Sea gadoid fishery consists on one of the above-mentioned grids with a minimum bar spacing of 55 mm and a codend with a minimum mesh size of 130 mm. Cod is the main target species in this fishery and its Minimum Legal Size (*MLS*) is 44 cm, whereas for other species like haddock and redfish, which is an important bycatch species in the fishery, the *MLS*s are 40 and 32 cm, respectively. Fishermen argue that the current regulations do not comply with the *MLS*s in the fishery and that high percentages of commercial fish are lost through the sorting system. Further, they maintain that as the regulations are "made for cod", the gear is highly inefficient to target haddock, a species that depending of the season and the quota availability, can become the main target species for some vessels participating in the fishery. This high inefficiency was corroborated by Brinkhof et al. (2020), who demonstrated that up to almost 80% of commercial-sized haddock can be sorted out by a system composed by a 55 mm bar spacing grid and a 130 mm diamond mesh codend.

The aim of the present study was twofold:

- Test a new Sort-V-like grid design constructed in plastic and determine whether its size selection properties were comparable to those of the Sort-V grid system.
- Study the effect of reducing grid bar spacing on the retention of cod, haddock and redfish with regard to *MLS*.

2.1.2. Materials and methods

Fishing trials

Fishing trails were conducted in southern area of the Barents Sea from 6th to 18th of December 2020 onboard R/V "Helmer Hanssen". For towing the trawls the vessel used a set of Injector Scorpion otter boards (each 3100 kg, 8m^2). The length of the sweeps was 60 m and they were connected with 3 m long backstraps followed by 7 m long connector wire to the otter boards. The sweeps where divided in 2 x 30 m and had a Ø53 cm steel bobbin in the middle to protect the sweeps from excessive abrasion. The sweeps were connected to a 46 m long ground gear.

The ground gear comprised of an 18.9 m long rock-hopper gear (Ø53 cm) in the middle, and a 14 m long (Ø 19 mm) chain with three equally spaced steel bobbins (Ø53 cm) on each side towards the sweeps. The rock hopper gear itseld was attached to the 19.2m long fishing line of the trawls. The trawls applied where two identical Alfredo 3 trawls. The headline of the trawls was 36.5 m long. The Alfredo 3 trawls are two-panels trawls, 420 meshes in circumference and built entirely 155 mm mesh size polyethylene (PE) netting.

The trawl belly was followed by a section with a Sort-V grid. Four different configurations were applied:

- Faeroese grid section with modified lifting panel and a 45 mm plastic grid.
- Faeroese grid section with modified lifting panel and a 55 mm plastic grid.
- Standard Sort-V grid section with a 45 mm steel grid.
- Standard Sort-V grid section with a 55 mm steel grid.

All grids had an overall length of 1650 mm and a width of 1234 mm. The mean ± standard deviation bar spacings for the grids tested was; 54.6 ± 0.6 mm and 44.1 ± 0.8 mm for the two plastic grids, and 54.8 ± 1.1 mm and 44.7 ± 1.3 mm for the two steel grids.

Between the grid section and the codend an extension piece was inserted. The codend was comprised of two-panels, and was 12 m long and 66 meshes in circumference. The codend was built of Ø8 mm hotmelt PE twine (Polar Gold), single braided with a nominal mesh size of 133. To isolate the selectivity trough the grid the selectivity in the codend was prevented by inserting a liner with mesh size of 52.2 ± 3.0 mm (mean ± SD). A grid cover was mounted over the escape outlet of the grid in order to catch the escapees. The grid cover had an inner mesh size of 45.2 ± 0.9 mm (mean ± SD) and was strengthened with a large mesh netting on the outside and equipped with seven floats to avoid blockage of the escape outlet (Fig. 2).

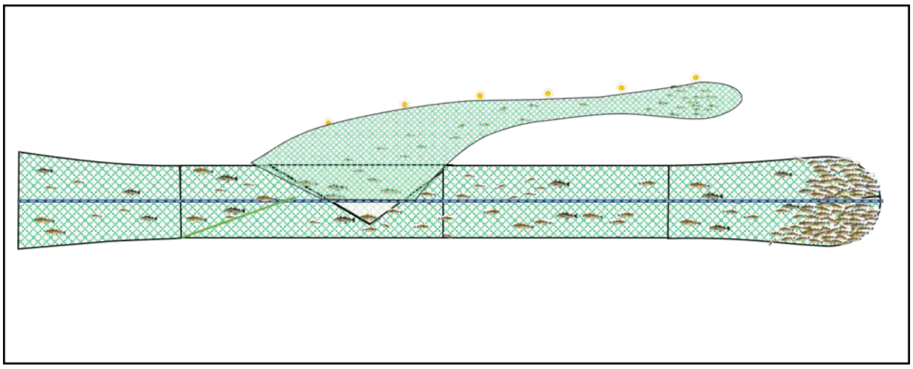


Figure 2. Experimental setup showing the Sort-V grid and the grid cover followed by an extension piece and a blinded codend.

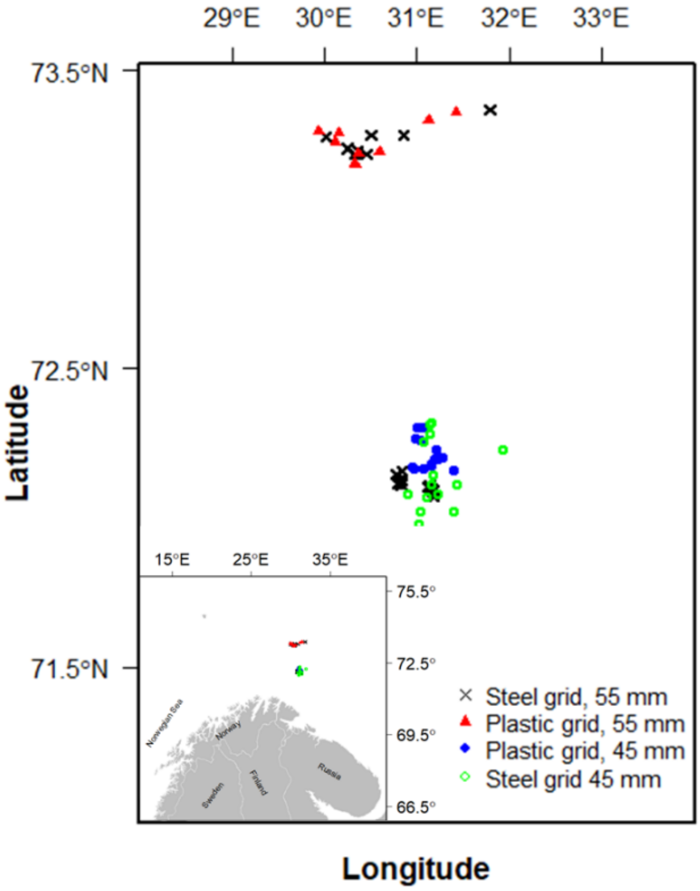


Figure 3. Overview over the area where the hauls were conducted.

Table 1. Overview over the hauls conducted showing type of grid, date, position, depth. towing time and number of cod, haddock and redfish caught in either the codend or cover.

					Cod		**Haddock**		**Redfish**	
Stnr	**Grid type**	**Date**	**Depth (m)**	**Towing time (hh:mm)**	**Codend**	**Cover**	**Codend**	**Cover**	**Codend**	**Cover**
729	55 mm steel	06.12.2020	279.26	1:32	82	42	3	17	3	28
730	55 mm plast	06.12.2020	328.9	1:30	159	56	7	20	24	71
731	55 mm plast	06.12.2020	331.71	1:33	92	20	4	11	121	229
732	55 mm steel	06.12.2020	329.68	1:31	166	64	5	21	146	195
733	55 mm steel	06.12.2020	331.62	1:31	132	54	6	30	33	91
734	55 mm plast	06.12.2020	328.51	1:31	356	88	22	27	31	28
735	55 mm plast	06.12.2020	334.95	1:32	423	146	48	84	40	37
737	55 mm steel	06.12.2020	310.63	1:32	207	74	10	54	25	60
738	55 mm steel	06.12.2020	290.41	1:34	266	107	9	27	50	120
739	55 mm plast	07.12.2020	335.65	1:30	210	111	34	54	65	68
740	55 mm plast	07.12.2020	303.29	1:30	270	99	25	45	103	76
741	55 mm steel	07.12.2020	326.83	1:30	282	69	31	31	132	55
742	55 mm steel	07.12.2020	298.32	1:32	184	111	11	32	31	94
743	55 mm plast	07.12.2020	314.84	1:30	368	88	28	47	74	79

744	55 mm plast	07.12.2020	313.82	1:30	165	50	16	69	20	37
746	55 mm steel	08.12.2020	311.13	1:30	293	76	6	29	147	209
764	45 mm plast	12.12.2020	311.61	2:00	148	6	193	73	8	4
765	45 mm plast	12.12.2020	303.17	2:01	179	3	178	146	13	4
766	45 mm plast	12.12.2020	310.39	2:02	174	14	191	101	13	7
767	45 mm plast	13.12.2020	298.95	2:00	183	10	153	73	6	5
768	45 mm plast	13.12.2020	312.81	2:00	139	4	183	126	5	8
769	45 mm plast	13.12.2020	302.15	1:58	218	5	160	85	20	15
770	45 mm plast	13.12.2020	297.18	2:01	231	6	207	64	40	40
771	45 mm plast	13.12.2020	310.12	2:00	251	4	261	120	18	17
772	45 mm plast	13.12.2020	302.91	2:00	235	13	240	115	23	13
773	45 mm plast	13.12.2020	309.64	2:00	268	6	240	114	15	2
774	45 mm plast	13.12.2020	304.84	2:00	262	12	237	84	10	15
775	45 mm plast	13.12.2020	297.12	2:04	340	8	238	111	20	13
776	45 mm plast	14.12.2020	299.87	2:00	320	6	252	103	23	16
777	45 mm plast	14.12.2020	303.48	2:00	299	4	255	80	26	2
779	45 mm steel	14.12.2020	299.12	1:30	442	11	261	124	2	4
780	45 mm steel	14.12.2020	300.06	1:00	260	7	186	84	9	12
781	45 mm steel	14.12.2020	300.32	1:02	340	15	341	110	20	20
783	45 mm steel	14.12.2020	297.68	1:00	529	8	320	147	9	13
784	45 mm steel	14.12.2020	255.57	1:01	522	11	329	63	29	17
785	45 mm steel	15.12.2020	310.37	1:03	71	8	88	98	6	27
786	45 mm steel	15.12.2020	334.37	1:30	62	11	81	120	2	15
787	45 mm steel	15.12.2020	322.96	1:30	80	11	147	147	5	14
788	45 mm steel	15.12.2020	320.93	2:00	136	19	176	277	9	34
789	45 mm steel	15.12.2020	323.76	2:00	128	23	182	246	7	29
790	45 mm steel	15.12.2020	317.92	2:00	111	9	151	245	8	37
791	45 mm steel	16.12.2020	320.16	2:00	129	8	126	203	4	30
792	45 mm steel	16.12.2020	312.24	2:00	153	14	235	217	11	12
793	45 mm steel	16.12.2020	308.42	2:00	180	23	179	245	9	23
794	55 mm steel	16.12.2020	317.53	2:00	204	44	96	347	13	33
795	55 mm steel	16.12.2020	321.58	2:00	312	45	292	422	5	17
796	55 mm steel	16.12.2020	313.93	2:00	315	39	329	353	7	22
797	55 mm steel	16.12.2020	321.17	2:02	226	65	164	596	10	80
798	55 mm steel	16.12.2020	319.06	2:00	164	39	115	448	6	38
799	55 mm steel	17.12.2020	317.76	2:00	228	47	149	571	13	56
800	55 mm steel	17.12.2020	320.79	2:03	223	53	192	504	11	37
801	55 mm steel	17.12.2020	319.42	2:02	105	40	67	312	3	54
802	55 mm steel	17.12.2020	321.87	2:00	161	50	86	356	12	58
803	55 mm steel	17.12.2020	330.8	2:00	183	55	142	348	10	30
804	55 mm steel	17.12.2020	322.74	2:00	281	52	175	368	8	30
805	55 mm steel	17.12.2020	322.78	2:01	405	55	251	401	12	40
806	55 mm steel	18.12.2020	321.06	2:00	280	40	197	454	15	31
807	55 mm steel	18.12.2020	331.85	2:00	257	72	223	621	-	-

Data analysis

* The data analysis was carried out following the procedure described in Jacques et al. 2019.

2.1.3. Results

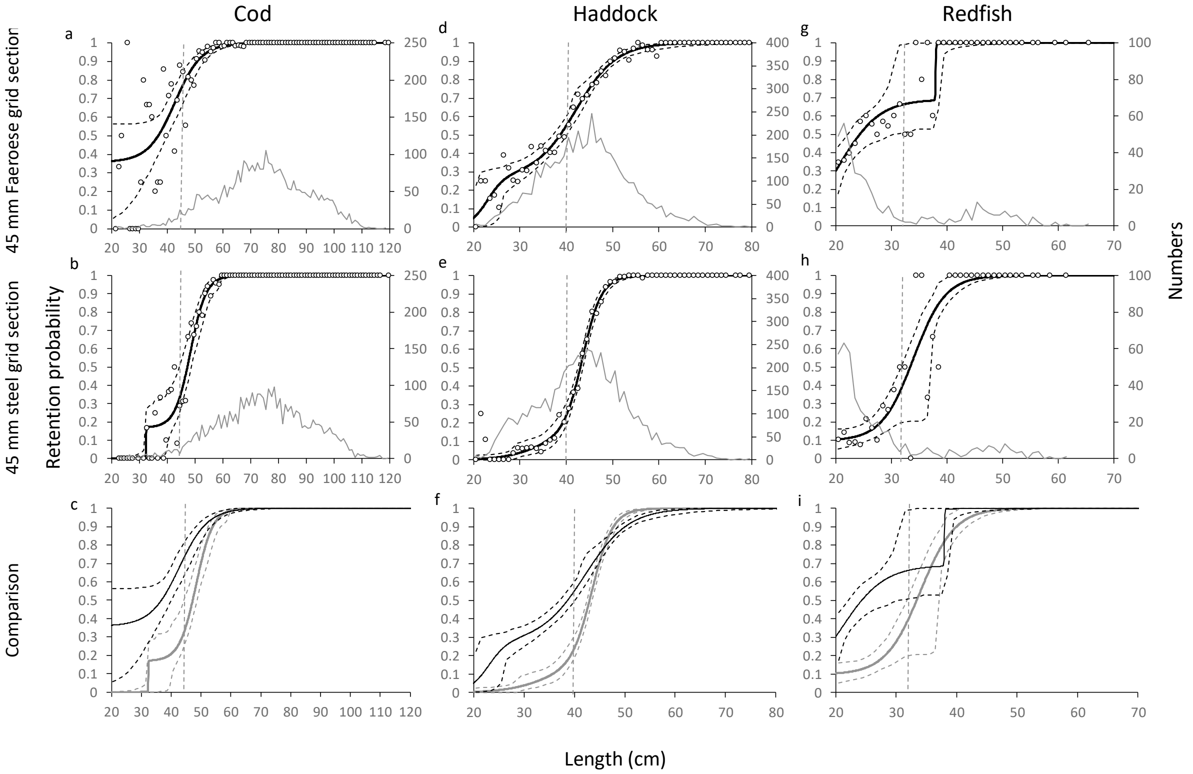


Figure 4: Retention probability with the standard Sort-V section with a 45 mm steel grid and the Faeroese section with a 45 mm plastic grid for cod (a-c), haddock (d-f) and redfish (g-i). In the comparison, the Faeroese section with a 45 mm plastic grid in black and the standard Sort-V section with a 45 mm steel grid in grey.

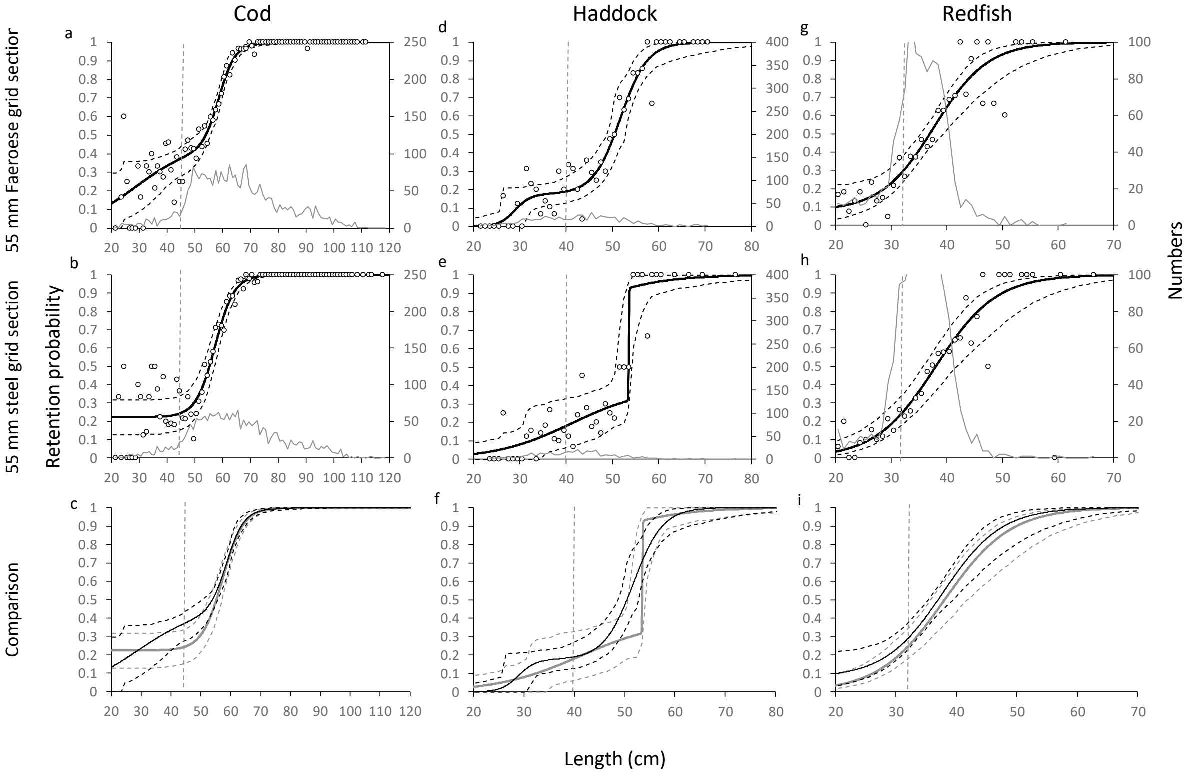


Figure 5: Retention probability with the standard Sort-V section with a 55 mm steel grid and the Faeroese section with a 55 mm plastic grid for cod (a-c), haddock (d-f) and redfish (g-i). In the comparison, the Faeroese section with a 55 mm plastic grid in black and the standard Sort-V section with a 55 mm steel grid in grey.

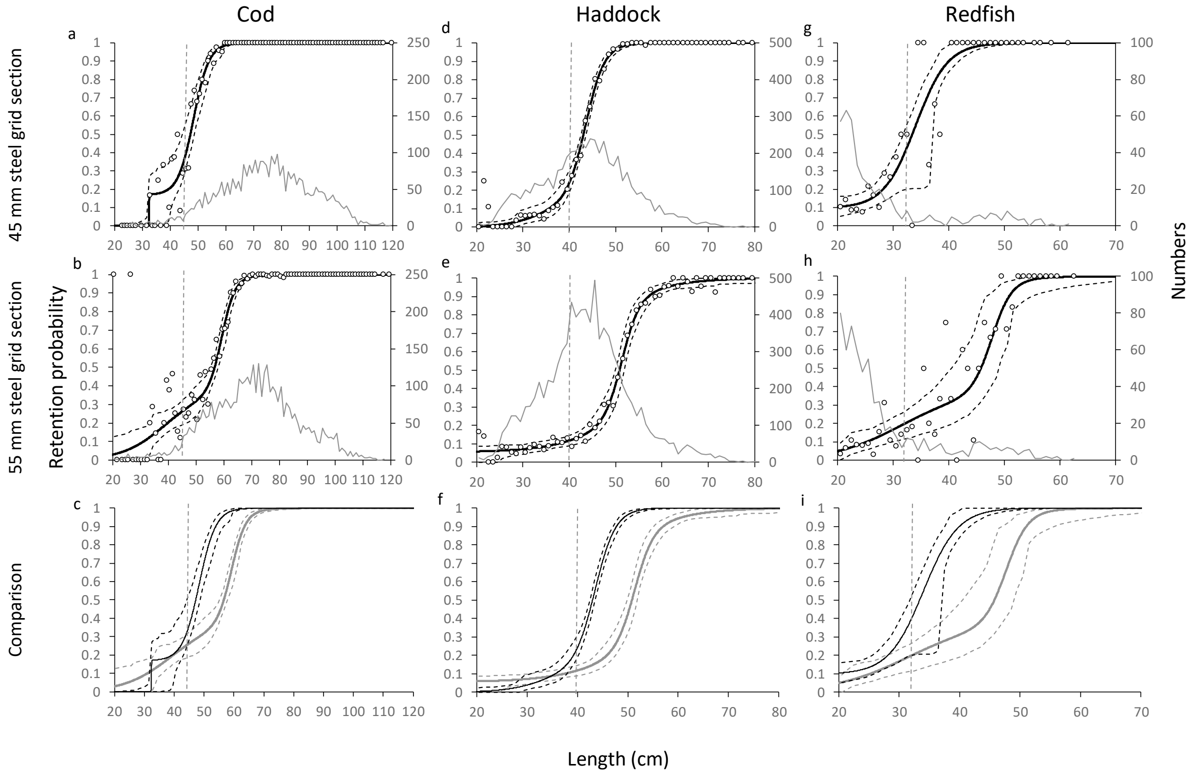


Figure 6: Retention probability with the 45 mm steel grid and the 55 mm steel grid for cod (a-c), haddock (d-f) and redfish (g-i). In the comparison, the standard Sort-V section with a 45 mm steel grid in black and the standard Sort-V section with a 55 mm steel grid in grey.

2.1.4. Discussion

The results from this study show that the grid sections imported from the Faeroe Islands which comprised of a plastic grid installed on a modified grid section, and that were was tested with bar spacings in 45 and 55 mm performed different to the Sort-V section that is compulsory in the fishery today. These differences were not significant for the 55 mm grid but they were significant for cod and haddock with the 45 mm grid. The data collected for the 45 mm grid were stronger than those collected with the 55 mm grid. The Faeroese grid retained significantly smaller fish, which could be partly attributed to the construction of the section and specifically the lifting panel. This could also be corroborated by underwater recordings, which showed that the lifting panel did not lead the fish towards the grid as well as in the steel grid sections. The concept of substituting the steel grid with a plastic/rubber grid in a Sort-V section is still interesting as it would solve several of the challenges (e.g. weight and maneuverability) of the existing grid concept. However, further work needs to be put into the development of a section, which could have as starting point a Sort-V system where the steel grid is substituted by an equivalent plastic grid and the floats removed.

As expected, the retention of the 45 mm steel grid differed significantly from that of the 55 mm mandatory grid.

* The extent of these differences is yet to be analyzed and indicators need to be calculated.

2.2. Vertical separation of cod and haddock I

The aim of our trials in December 2020 and March 2021 (Section 4.3) was to separate cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) by utilizing their natural behaviour and guide them into separate codends. A vertical panel was inserted in the trawl and. The 7 m long aft end of the panel was gradually turned 90o to be able to align the two codends side by side for practical handling. Fish entering the upper part of the trawl was guided into a 120 mm codend, while those fish entering the lower part of the trawl was led into a 130 mm codend.

Previous trials with two-level bottom trawls in the North Sea (Main and Sangster, 1985;, Krag et al. 2009) and the Barents Sea with a two-level trawl (Valdemarsen et al. 1985), and with demersal seines (Vollstad, 2003; Isaksen and Ingólfsson, 2014), proved and suggested that it is possible to separate species like cod and haddock by a vertical panel along the trawl body and guide them into two (separate) codends (Fig 7) . This principle aimed at avoiding "choke species" (illegal to catch) by keeping one of the codends open, to reduce the number of undersized fish

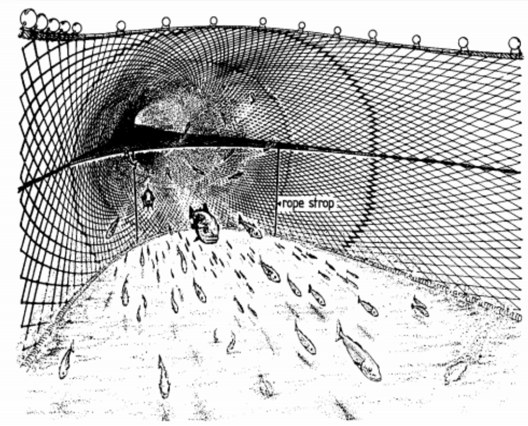


Fig. 7. Illustration of a two-level trawl as described by Main and Sangster, 1985.

by changing the selection properties by using different mesh sizes in the codends or as in our trials use more effective and species adjusted mesh sizes for cod and haddock in each codend.

We based our design on the technical setup used by Valdemarsen et al. 1985, where they examined an Alfredo No 3 two-level trawl using variable height of the separating panel (0.5, 0.75, 1.0 and 1.5m over the fishing line). Restricted with time we decided to use a small/short separator panel to avoid loss of valuable towing time if damaging the panel or the trawl. The vertical panel covered the last 4 m of the aft section of the trawl belly. The 7 m long extension of the separating panel gradually turned horizontal and ended in two openings where the codends were sewn on (Fig 8). We estimated that the distance between the vertical panel and the lower panel was close to 0.8 m.

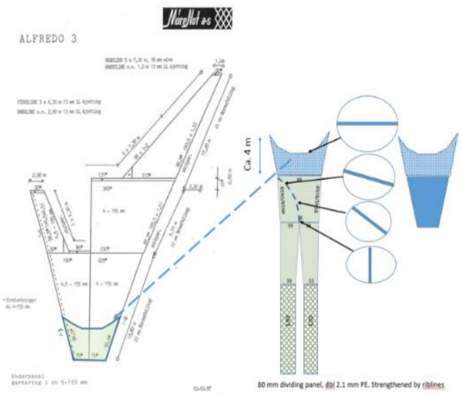


Fig. 8. The design of the two-level trawl used in December 2020.

The vertical panel was observed to divide the trawl belly as intended (see photo below), but the few hauls made showed that cod and haddock had little or no preference for compartments and entered the upper and lower section of the two-level trawl more or less in equal numbers. It was also clear from hauls during filming (GoPro Hero 8 with artificial light) that cod and haddock entered the trawl equally in the upper and lower section. As artificial white and red light may affect fish behaviour, the observations hauls were excluded from the evaluation of the system. No measurements of fish were made since the obvious conclusion was that the system didn’t work. The results are very different from the North Sea trials (Main and Sangster, 1985), but very close to the findings by Valdemarsen et al., 1985.

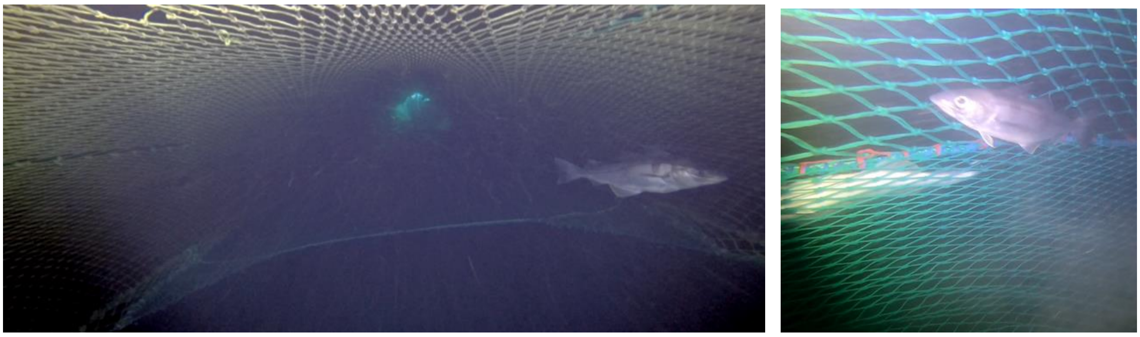


Fig. 9. Photo left side: The front of the vertical panel with a haddock on the “correct side” in the two-level trawl. Photo right side: Haddock and cod on correct side as entering the codends.

3. Cruise January 2021 onboard R/V Helmer Hanssen

3.1. Test of codends with shortened lastridge ropes

3.1.1. Summary

In many trawl fisheries, codend size selectivity is supplemented by adding selection devices to the gear. In the Barents Sea gadoid fishery, combining diamond mesh codends with sorting grids is compulsory. However, the use of grids increases the costs and complexity of the gear, causing discontent among fishermen and prompting researchers to seek alternative solutions. In this study, we tested the effect of shortening the lastridge ropes of two diamond mesh codends with different mesh sizes on the size selectivity of cod (*Gadus morhua*), haddock (*Melanogramus aeglefinnus*), and redfish (*Sebastes* spp.). Shortening the lastridge ropes increased the mesh opening during the fishing process, which significantly improved the size-selective properties of the codends. Therefore, codends with shortened lastridge ropes may be a simpler alternative to sorting grids in this fishery, and they may be applicable to many other fisheries in which additional selection devices are used.

3.1.2. Introduction

Diamond mesh codends are the most widespread and simplest size-selection device used in demersal trawls, and in some fisheries, size selectivity relies solely on the selective properties of this type of codend (Cheng et al. 2019). However, diamond mesh codends can pose challenges and yield unsatisfactory results (Robertson and Stewart 1988; Sala et al. 2008;

Wienbeck 2011). For example, as the codend catch builds up, tension increases and the longitudinal forces in the mesh bars close the codend meshes, thereby limiting their selective properties (Robertson and Stewart 1988; Herrmann 2005a, b).

The most obvious approach to solving codend selectivity issues would be to modify the codend itself. However, in many fisheries the approach adopted has been to insert additional devices into the gear, such as square mesh panels (Graham et al. 2003; Herrmann et al. 2015; Cuende et al. 2020) or sorting grids (Sistiaga et al. 2008; Brinkhof et al. 2020), to supplement codend size selectivity. One such fishery is the Barents Sea gadoid trawl fishery, which is one of the most important demersal fisheries in the world (Bergstad et al. 1987; Olsen et al. 2010). In this fishery, the diamond mesh codend is supplemented by a rigid sorting grid, which became compulsory in 1997 due to unsatisfactory size selection of the diamond mesh codend alone (Larsen and Isaksen 1993). The current compulsory size-selection gear is a dual system composed of a sorting grid with a minimum bar spacing of 55 mm and a subsequent diamond mesh codend with a minimum mesh size of 130 mm (Norwegian Directorate of Fisheries 2017). Fishermen can choose among three different sorting grid systems (Sort-X, Sort-V, and Flexigrid) that have been developed over time since the first trials were conducted in the early 1990s (Larsen and Isaksen 1993; Grimaldo et al. 2016).

The fishing industry would like to remove the mandatory use of grids from the regulations because they are expensive, heavy, and can substantially influence water flow in the extension piece and codend (Grimaldo et al. 2016). Reduced water flow in the aft part of the trawl can lead to fish accumulation, which can result in section breakage (Sistiaga et al. 2016) and failure of catch limiters and catch sensors (Grimaldo et al. 2014). In addition, the three grid systems may not be equally efficient, and their performance can vary substantially depending on factors such as catch densities and whether the section is constructed of two or four panels (Sistiaga et al. 2016; Brinkhof et al. 2020).

The mandatory use of selection grids in the Barents Sea demersal trawl fishery has been questioned since it was made compulsory in 1997 (Jørgensen et al. 2006). Simple codend modifications or additional devices such as exit windows or square mesh sections have been tested as potential alternatives (Jørgensen et al. 2006; Grimaldo et al. 2008; Grimaldo et al. 2018). Although some of the sorting devices have shown selection properties similar to those of the sorting grids, issues related to how to mount the devices and how to objectively monitor and control their use have prevented their implementation. Another approach that does not require additional devices and is relatively simple to implement and control is to attach short lastridge ropes in the codend. Lastridge ropes are ropes attached to the selvedges of the codend, and they are normally slightly shorter than the codend netting (e.g., typically 0–5% in the Barents Sea). When the catch builds up, most of the load is carried by these ropes rather than by the netting in the codend. By shortening the lastridge ropes further, they would bear the load of the catch to a greater extent than in a typical codend. Consequently, the tension in the codend netting would remain low as the catch accumulates, resulting in more open meshes during fishing, which should improve the selective properties of the codend (Isaksen and Valdemarsen 1990; Lök et al. 1997; Ingolfsson and Brinkhof 2020).

Cod (*Gadus morhua*) and haddock (*Melanogramus aeglefinnus*) are the main target species in the Barents Sea demersal trawl fishery, and redfish (*Sebastes* spp.) are among the main bycatch species. Large cod and haddock often acquire a higher price per kilogram than smaller individuals, and fishermen generally aim to maximize the revenue from their limited quotas. Therefore, fishermen in this area often are interested in only catching fish well above the minimum legal size (*MLS*), which is 44 cm for cod, 40 cm for haddock, and 32 cm for redfish. These three fish have substantial morphological (Sistiaga et al. 2011; Herrmann et al. 2012) and behavioral differences (Engås and Godø 1989; Larsen et al. 2016). Thus, the effects of gear modifications on size-selection properties and catch patterns vary among them.

Although earlier studies have documented the performance of codends with shortened lastridge ropes compared to other gear (Lök et al. 1997; Ingolfsson and Brinkhof 2020), research documenting the potential gains of applying shortened lastridges in the codend is limited (Isaksen and Valdemarsen 1990). Thus, the objectives of this study were to investigate the effect of shortening the lastridge ropes on codends with different mesh sizes and to evaluate how the changes affect the selectivity and catch patterns of cod, haddock, and redfish in the Barents Sea demersal trawl fishery. Considering the *MLS* and exploitation pattern desired by fishermen for the different species involved, we also investigated whether codends with shortened lastridge ropes could realistically replace the grid system required in the fishery today. Specifically, the research was designed to answer the following research questions:

- Do shortened lastridge ropes modify the selection properties of diamond mesh codends for cod, haddock, and redfish? If so, then to what extent?
- Is it possible to explain the selectivity results obtained for cod, haddock, and redfish by their species-specific characteristics and potential changes in the codend meshes generated by shortening the lastridge ropes?
- Can shortened lastridge codends provide the desired catch patterns for cod, haddock, and redfish so that they could replace the grid system required in the Barents Sea demersal trawl fishery?

3.1.3. Materials and methods

Study area, experimental design, and data collection

Experimental fishing was conducted onboard the research vessel *Helmer Hanssen* (63.9 m long, 4080 HP) from the 8th to the 16th of January, 2021 in the southern part of the Barents Sea (71°22'65"N–72°08'30"N, 25°48'92"E–30°13'44"E). The experimental fishing was conducted using an Alfredo 5 twin-body trawl (trouser-trawl) combined with a set of Injector Scorpion trawl doors, each weighing 3100 kg and with an area of 8 m^2. The trawl doors were connected to the sweeps with 3 m long backstraps followed by 7 m long connector wires. The sweeps were 2 x 30 m long and divided by a Ø53 cm steel bobbin in the middle to protect them from excessive abrasion. The sweeps were connected to a 48 m long ground gear, which consisted of a 14 m long chain (Ø19 mm) with four equally spaced bobbins (Ø53 cm) on each side with a rock-hopper gear in the middle. The rock-hopper gear was 21 m long and equipped with Ø53 cm discs. The headline in the trawl was 38 m long, and it was equipped with 170 floats (8"). The trawl net itself was a modified 155 mm, two-panel Alfredo 5 twin-body trawl. A vertical panel (# 80 mm) was inserted in the front part of the trawl body to divide it into two equal sections. At the end of the vertical net, the trawl body was split into two equal 23.3 m long tapered funnels (Fig. 10a). Each funnel was followed by a 14.1 m long extension piece, which took the place of the grid section that is compulsory in the commercial fishery. The codends were mounted directly onto the extension pieces and consisted of two panels made of single braided polyethylene hotmelt twine (Ø8 mm). Each codend was 12 m long and 60 free meshes in circumference. The two codends had different mesh sizes: 128.23 ± 3.97 mm and 137.08 ± 2.28 mm. These two mesh sizes represent the minimum mesh size used by the fleet in the fishery (130 mm), and a codend with approximately 1 cm bigger meshes. The selvedges of the codends were strengthened with Ø32 mm thick lastridge ropes. During the first part of the experimental period, the two codends were tested with a regular lastridge rope configuration (no shortening), whereas in the second part of the experimental period the lastridge ropes in the last 6 m of both codends were shortened by 15%.

The entire length of the codends was covered with small-meshed covers that caught fish escapees. To ensure that the covers stayed clear of the codend netting, the front part of each of the covers was equipped with six floats, three kites, and a 12 kg piece of chain on the top, side, and bottom part of the codend, respectively (Fig. 10b). Further, each of the covers had 12 kites attached to the cover around the bulk of the catch in the codend. The covers had a nominal mesh size of 50 mm and were strengthened with an outer layer of large-meshed netting in the aft part.

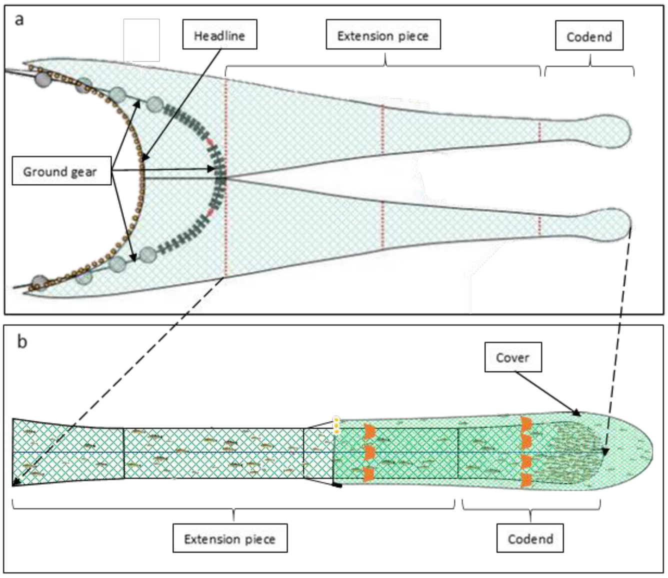


Figure 10: Illustration showing the twin-body trawl (a) and the configuration of the covers over the codends (b).

The performance of the trawl was monitored continuously with a set of trawl door sensors, a sensor measuring trawl height, and a catch volume sensor. During the trials, the catch from each compartment was kept in separate holding bins. The length of all cod, haddock, and redfish above 20 cm was measured to the nearest centimeter below.

Modeling and estimation of the size selection in the codends

The data for each species were analyzed separately using the method described here. The experimental design (Fig. 10) applied to test the codends enabled us to analyze the catch data as binominal data. The numbers of individuals per length class, retained either by the codend cover or by the codend itself, were used to estimate the size selection in the codend (i.e., length-dependent retention probability). The size selectivity between hauls for the same codend is expected to vary (Fryer 1991). However, we were interested in the size selection averaged over hauls because it would provide information about the average consequences for the size selection process when using the codend in the fishery. We tested different parametric models of the form $r_{codend}(l, \boldsymbol{v_{codend}})$ for the codend size selection, where $\boldsymbol{v_{codend}}$ is a vector consisting of the parameters in the model. The purpose of the analysis was to estimate the values of the parameters in $\boldsymbol{v_{codend}}$ that maximized the likelihood for the experimental data (averaged over hauls) to be obtained. For this purpose, the following expression was minimized, which corresponds to maximizing the likelihood of observing the experimental data:

$$-\sum_{j=1}^{m}\sum_{l}\left\{nC_{lj} \times ln\left(r_{codend}(l, \boldsymbol{v_{codend}})\right) + nCC_{lj} \times ln\left(1.0 - r_{codend}(l, \boldsymbol{v_{codend}})\right)\right\} \quad (1)$$

The outer summation in expression (1) comprises the hauls j (from 1 to m) conducted with the specific codend, and the inner summation is over the length classes l in the data.

Four different models were chosen as basic candidates to describe $r_{codend}(l, \boldsymbol{v_{codend}})$ for each codend and species individually: Logit, Probit, Gompertz, and Richard. The first three models are fully described by the selection parameters L50 (length of fish with 50% probability of being retained) and SR (difference in length between fish with 75% and 25% probability of being retained, respectively), whereas the Richard model requires an additional parameter (D) that describes the asymmetry of the curve. The formulas for the four selection models and additional information can be found in Lomeli (2019). Evaluating the ability of a model to describe the data sufficiently well was based on estimating the corresponding p-value, which expresses the likelihood of obtaining at least as big a discrepancy between the fitted model and the observed experimental data by coincidence. Therefore, for the fitted model to be a candidate to model the size-selection data, this p-value should not be < 0.05 (Wileman et al. 1996). In case of a poor fit statistic (p-value < 0.05), the residuals were inspected to determine whether the poor result was due to structural problems when modeling the experimental data with the different selection curves or if it was due to overdispersion in the data (Wileman et al. 1996). The best model among the four considered was selected by comparing their Akaike information criterion (AIC) values. The model with the lowest AIC value was selected (Akaike 1974).

Once the specific size-selection model was identified for each species and codend configuration, bootstrapping was applied to estimate the confidence limits for the average size selection. We used the software tool SELNET (Herrmann et al. 2012) for the size-selection analysis, and the double bootstrap method was implemented in the tool to obtain the confidence limits for the size-selection curve and the corresponding parameters. This bootstrapping approach is identical to the one described in Millar (1993) and takes into consideration both within-haul and between-haul variation. The hauls for each codend configuration were treated as a group of hauls. To account for between-haul variation, an outer bootstrap resample with replacement from the group of hauls was included in the procedure. Within each resampled haul, the data for each length class were bootstrapped in an inner bootstrap with replacement to account for within-haul variation. Each bootstrap resulted in a "pooled" set of data, which was then analyzed using the identified selection model. Thus, each bootstrap run resulted in an average selection curve. For each species analyzed, 1000 bootstrap repetitions were conducted to estimate the Efron percentile 95% confidence limits (Efron 1982; Herrmann et al. 2012).

Estimation of difference in size selectivity between codends

The difference in size selectivity $\Delta r(l)$ between two codends *x* and *y* was estimated by:

$$\Delta r(l) = r_y(l) - r_x(l) \qquad (2)$$

where *x* and *y* represent the different codends, respectively. The 95% confidence intervals (CI) for $\Delta r(l)$ were obtained based on the two bootstrap population results for $r_x(l)$ and $r_y(l)$, respectively. As they were obtained independently of each other, a new bootstrap population of results for $\Delta r(l)$ was created using the procedure described in Larsen et al. (2018):

$$\Delta r(l)_i = r_y(l)_i - r_x(l)_i \;\; i \in \; [1 \ldots 1000] \qquad (3)$$

Finally, based on the bootstrap population, Efron 95% percentile confidence limits were obtained for $\Delta r(l)$ as described above.

Exploitation pattern indicators for the codends

To investigate how the different codend configurations affected the capture pattern for each species separately, we estimated the value of three exploitation pattern indicators, nP^{-}, nP^{+}, and *nDiscard* (discard ratio). These indicators are often used in fishing gear size selectivity studies to supplement assessment solely based on selectivity curves (Santos et al. 2016; Sala et al. 2017; Cheng et al. 2019; Kalogirou et al. 2019; Melli et al. 2020). To estimate these exploitation pattern indicators, we first applied the predicted size-selection curves for each codend to the population of each species entering the fishing gear, which was estimated from the population entering the gear summed over all codends during the experimental fishing. The population size structure $nPop_l$ for each individual species was obtained based on the data for all hauls from all codend designs by summing catches in the codend and cover. Uncertainties in populations were obtained by double bootstrapping following the approach described in Melli et al. (2020). We then estimated the percentage of individuals retained for individuals below (nP^{-}) and above (nP^{+}) a specified *MLS*, respectively, for each codend. We also estimated *nDiscard*, which is a measure of the number of undersized fish relative to the number of fish in the haul. For cod and haddock, we estimated the indicators for the current *MLS* (44 and 40 cm, respectively) and for an *MLS* of 50 cm for cod and 45 cm for haddock, which represents the scenario in which fishermen are interested in catching fish only well above the *MLS*. Ideally, nP^{-} and *nDiscard* should be low (close to 0), while nP^{+} should be high (close to 100). The indicators were estimated for the different codends by:

$$
\begin{aligned}
nP^{-} &= 100 \times \frac{\sum_{l<MLS}\{r_{codend}(l,\boldsymbol{v_{codend}}) \times nPop_l\}}{\sum_{l<MLS}\{nPop_l\}}, \\
nP^{+} &= 100 \times \frac{\sum_{l>MLS}\{r_{codend}(l,\boldsymbol{v_{codend}}) \times nPop_l\}}{\sum_{l>MLS}\{nPop_l\}},
\end{aligned}
\qquad (4)
$$

$$nDiscard = 100 \times \frac{\sum_{l<MLS}\{r_{codend}(l, \boldsymbol{v}_{\boldsymbol{codend}}) \times nPop_l\}}{\sum_{l}\{r_{codend}(l, \boldsymbol{v}_{\boldsymbol{codend}}) \times nPop_l\}}$$

All indicators (nP^-, nP^+, and *nDiscard*) were estimated with uncertainties for each codend using the bootstrap set for $r_{codend}(l, \boldsymbol{v}_{\boldsymbol{codend}})$ and $nPop_l$. Specifically, based on Herrmann et al. (2018), the bootstrap set for estimating indicator values was obtained based on each bootstrap repetition result in which $r_{codend}(l, \boldsymbol{v}_{\boldsymbol{codend}})$ and $nPop_l$ were applied simultaneously in Eq. (4). Finally, based on the resulting bootstrap set, 95% CIs were obtained for each of the indicators. All analyses of the exploitation pattern indicators were conducted using SELNET (Herrmann et al. 2012).

Comparison with the gear currently used in the fishery

To assess the performance of the four codend configurations tested in this study relative to the gear currently used in the Barents Sea, we first estimated the exploitation pattern indicators for the Sort-V and Flexigrid grid systems combined with a diamond mesh codend for cod, haddock, and redfish. We then compared these results to those obtained in the present study for the four codend configurations tested. The selectivity data used to estimate the indicators for cod and haddock with a Sort-V grid combined with a diamond mesh codend were obtained from Sistiaga et al. (2010), whereas the data for the Flexigrid and codend system for these two species were obtained from Brinkhof et al. (2020). Note that the codend used together with the Sort-V grid in Sistiaga et al. (2010) had a mesh size of 135 mm, which was the minimum mesh size in the codend at the time. The selectivity data used for redfish were presented in Herrmann et al. (2013). As the exploitation pattern indicators depend on the fish population in the area at the time the trials are conducted ($nPop_l$), the $nPop_l$ used to estimate the indicators for cod, haddock, and redfish with the grid systems was the same as that used to estimate the indicators for the four codend configurations tested in the present study.

Understanding codend size selection based on fish morphology and mesh geometry

Mesh size and mesh openness affect selectivity in diamond mesh codends (Herrmann 2005a, b; Herrmann and O'Neill 2005; Herrmann et al. 2007; O'Neill and Herrmann 2007; Herrmann et al. 2009). During trawling, codend meshes are stretched by hydrodynamic drag forces that act primarily on the catch accumulated in the aft end of the codend (Herrmann 2005b; Herrmann et al. 2006), and it is unlikely that fish trying to escape through the codend meshes will be able to deform the netting while tension is increasing in the codend. Thus, during towing and haul back the meshes will generally maintain their diamond shape. However, when the codend is at the surface with low or no tension, the meshes can be both wide open (up to 90 degrees) and slack, which could give fish trying to escape the chance to distort the mesh shape to fit their cross-sectional shape and escape through it (Herrmann et al. 2016).

FISHSELECT is a framework of methods, tools, and software developed to determine if a fish can penetrate a certain mesh shape and size in fishing gear (Herrmann et al. 2009). Through computer simulations, FISHSELECT enables estimation of the size selectivity for a certain species by comparing the morphological characteristics of the fish to the shape and size of the mesh. FISHSELECT enables simulation of the situation in which the mesh shape cannot be deformed by fish trying to escape through it (stiff mesh state) as well as the scenario in which the mesh is tensionless and can potentially be fully deformed by the effort of the fish while trying to escape (slack mesh state) (Herrmann et al. 2016).

Herein, we applied the FISHSELECT methodology to estimate the size-selective potential for the diamond mesh codends used during the experimental fishing. Application of FISHSELECT to simulate size selectivity through codend meshes for a species requires: i) a morphological model describing the cross-sections of importance for size selection of the species and ii) a model describing how and to what extent the fish cross-sections can be squeezed when trying to pass through a mesh. The FISHSELECT models necessary to study cod, haddock, and redfish size selectivity in diamond mesh codends for the Barents Sea demersal trawl fishery were already available from studies conducted by Sistiaga et al. (2011) and Herrmann et al. (2012). Based on these FISHSELECT models, we simulated the size selection in stiff diamond meshes with a mesh size identical to the two codends applied in the experimental fishing. Mesh opening angles between 10 and 90 degrees, in 10 degrees increments, were tested to establish the potential size selection in the codend and its dependency on the mesh opening angle. In addition, we simulated the potential size selection for slack meshes of the same mesh size. For each simulated size-selection data set obtained in this way, we fitted a logit selection model to obtain a size-selection curve. It is likely that fish will have multiple chances to attempt to escape, especially in the catch accumulation zone (Herrmann 2005a). If unsuccessful in a prior attempt, it is likely that decisive attempts will not be represented by the average mesh size but instead by meshes biased to some extent towards the maximum mesh size available in the codend. To account for this scenario in the simulations, we considered mean mesh sizes of 128 and 137 mm as well as mesh size + 2 times the standard deviations as an estimate for maximum mesh size for each of the codends (i.e. 134 and 142 mm, respectively).

We also investigated whether the experimental size-selection data for cod, haddock, and redfish obtained for the different codends in the sea trials could be understood based on the FISHSELECT simulations. Therefore, we evaluated whether the experimental size-selection curves based on the data collected during the sea trials could be replicated by simulating scenarios assuming different combinations of mesh states (i.e. mesh sizes and opening angles). We considered stiff diamond meshes for both the mean mesh sizes and the mean mesh sizes + 2 times the standard deviation for opening angles between 10 and 90 degrees. We also considered slack meshes for all four mesh sizes. We then identified the combination of varying mesh openness and state that was best able to reproduce the experimental size-selection curves obtained during the experimental fishing for each species for each codend separately.

To conduct this analysis, we used the selection curves, with CIs and retention lengths, obtained from the analysis of the sea trial data and the simulated retention data for different mesh openness and different mesh states from FISHSELECT. We estimated the contributions needed from the different retention data to obtain combined selection curves that best fitted the experimentally obtained data. This procedure is identical to the one applied by Herrmann et al. (2013, 2016) and Cuende et al. (2020), who provide detailed information on the technical aspects of the method.

3.1.4. Results

Overview of sea trials

We conducted 31 hauls during the experimental period, 6 of them with the 128 mm and 137 mm codends in the standard configuration (without shortened lastridge ropes) and 25 with the same codends in the shortened lastridge configuration. In total, we measured 12,938 cod, 12,162 haddock, and 3119 redfish during the trials (Table 2).

Table 2: Overview of the hauls conducted during the experimental sea trials and the numbers (*n*) of cod, haddock, and redfish retained in the codend (CD) and cover (C) in each haul. STD is the standard configuration (non-shortened lastridge ropes), and SL is the codend with shortened lastridge ropes.

Haul nr	**Duration tow (min)**	**Depth (m)**	**Gear**	**Cod 128 mm**		**Cod 137 mm**		**Haddock 128 mm**		**Haddock 137 mm**		**Redfish 128 mm**		**Redfish 137 mm**	
				***n*CD**	***n*C**	***n*CD**	***n*C**	***n*CD**	***n*C**	***n*CD**	***n*C**	***n*CD**	***n*C**	***n*CD**	***n*C**
1	188	315.73	STD	90	10	86	12	131	66	105	75	17	99	12	95
2	149	328.07	STD	116	5	117	16	110	51	90	87	11	94	7	84
3	173	311.19	STD	168	6	207	8	176	72	226	129	31	123	94	94
4	151	287.28	STD	68	3	97	6	115	94	187	114	29	6	24	12
5	124	345.00	STD	54	4	53	0	49	27	56	19	230	101	238	156
6	150	324.05	STD	158	8	209	18	127	61	192	110	81	97	71	169
7	130	254.28	SL	247	17	300	25	145	55	118	95	13	9	17	17
8	120	294.23	SL	108	2	131	8	73	39	78	43	11	7	18	4
9	145	255.55	SL	266	15	297	28	174	117	138	147	16	6	12	8
10	129	315.95	SL	291	3	319	16	148	67	139	108	14	7	24	16
11	120	237.82	SL	190	14	170	15	149	38	118	72	11	10	23	27
12	129	305.34	SL	246	14	391	39	131	65	158	121	20	2	20	9
13	122	321.79	SL	49	2	71	9	43	7	32	31	4	2	7	2
14	120	298.94	SL	108	6	121	12	83	64	91	57	13	2	9	5
15	120	261.87	SL	234	11	293	30	200	141	183	236	13	12	8	10
16	122	311.80	SL	218	3	307	27	158	103	164	206	21	6	5	13
17	121	308.68	SL	167	8	200	11	147	122	122	154	16	7	9	7
18	124	272.86	SL	192	7	259	27	102	48	125	127	11	11	16	13
19	120	312.52	SL	183	11	223	14	133	96	100	128	14	9	25	9
20	120	279.67	SL	222	10	264	34	141	72	153	171	17	6	11	17
21	128	301.11	SL	190	10	226	16	133	101	120	177	10	5	6	15
22	121	282.78	SL	119	3	174	25	90	49	79	126	16	14	14	10
23	125	298.49	SL	199	4	211	9	105	52	89	69	11	6	6	7
24	137	278.92	SL	109	7	146	1	70	38	69	65	8	2	10	6

25	121	299.40	SL	120	2	138	12	111	35	78	47	12	4	6	7
26	123	280.12	SL	162	6	212	16	117	76	117	117	15	13	9	14
27	126	273.58	SL	227	4	283	0	121	62	90	77	19	12	10	20
28	121	261.98	SL	393	10	495	31	128	68	134	111	19	4	7	22
29	125	298.08	SL	199	5	217	14	84	44	70	72	14	16	13	24
30	147	252.07	SL	198	2	243	18	37	20	54	57	9	27	8	19
31	130	266.45	SL	226	2	236	14	12	14	12	20	7	6	3	8

Size selectivity results

The size selectivity analysis results showed primarily that the models used to represent the data for all four codend configurations tested for cod, haddock, and redfish were adequate. In all cases, the *p*-value for the model with the lowest AIC value among the models considered was > 0.05, which indicates that the difference between the experimental points and the model used in every case could be coincidental (Table 3). This result was corroborated by the selectivity curves, which fitted the experimental data well in every case (Fig. 11).

Table 3: Selection model, selectivity parameters, and fit statistics for the four codend configurations tested and the three species sampled during the sea trials. *d* represents the asymmetry parameter in the Richard model (Lomeli et al., 2019).

Species	**Lastriges**	**Mesh size**	**Model**	**L50**	**SR**	***D***	**Deviance**	**DOF**	***p*-Value**
Cod	STD	128 mm	Logit	41.20	8.75	*	34.00	79	>0.999
		137 mm	Richard	44.29	12.28	0.19	39.17	82	>0.999
	SL	128 mm	Probit	41.79	9.63	*	53.14	92	>0.999
		137 mm	Logit	49.14	6.13	*	37.89	88	>0.999
Haddock	STD	128 mm	Probit	39.20	7.14	*	21.71	52	0.993
		137 mm	Richard	41.07	6.75	0.63	30.30	49	0.984
	SL	128 mm	Richard	40.53	6.75	0.67	50.01	54	0.629
		137 mm	Richard	45.12	6.31	0.62	38.81	58	0.975
Redfish	STD	128 mm	Richard	32.77	6.38	0.60	37.09	35	0.373
		137 mm	Richard	35.15	9.05	0.13	8.47	37	>0.999
	SL	128 mm	Richard	38.57	7.60	0.19	41.60	39	0.355
		137 mm	Richard	42.47	6.51	0.35	42.46	40	0.366

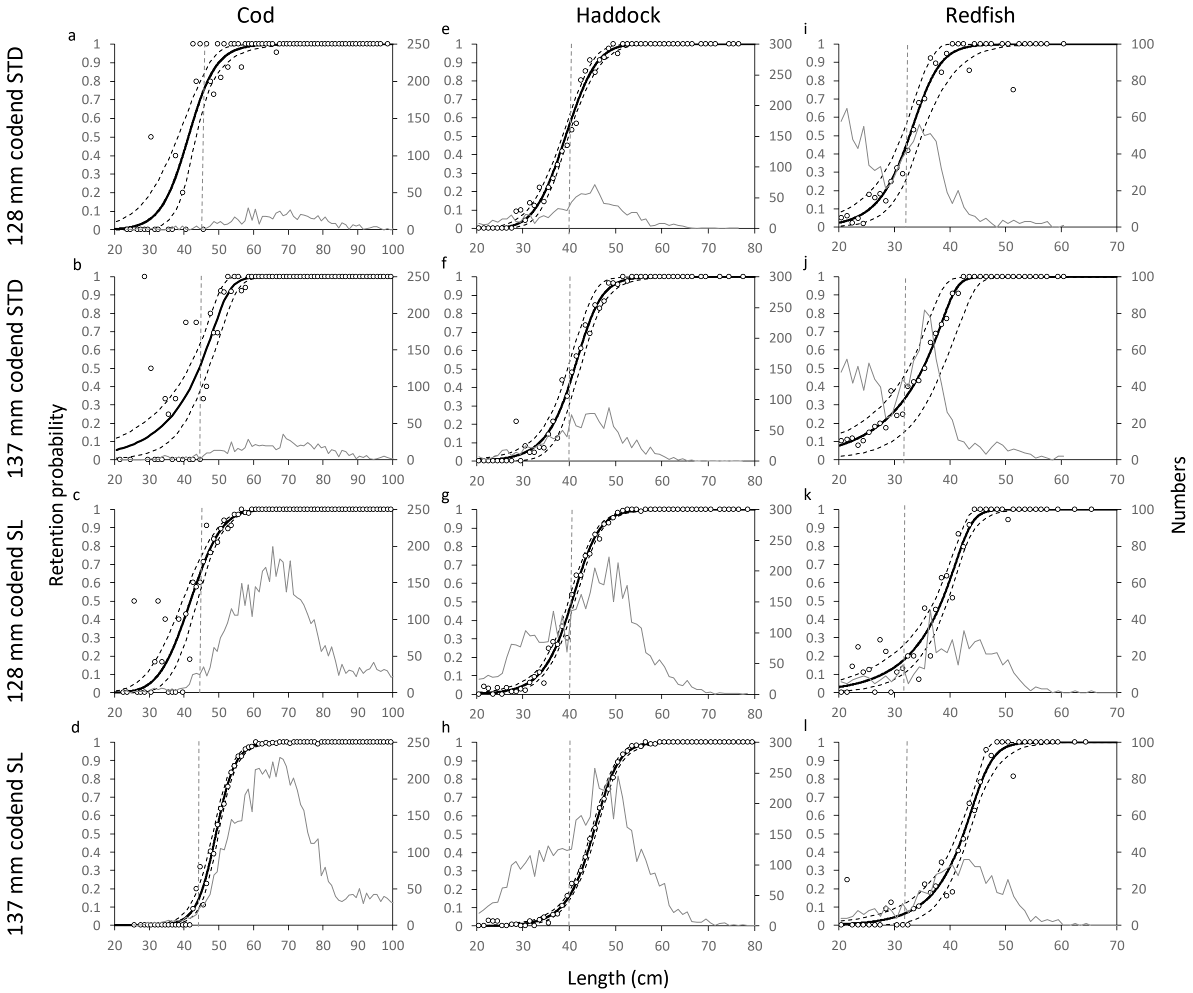


Figure 11: Length-dependent retention probabilities for cod, haddock, and redfish with the four codend configurations tested during the trials. In each plot, the circles represent the experimental observations, the solid curve the represents the models fitted to the data, and the stippled curves represent the 95% CIs. The grey line represents the population fished by the gear (codend + cover). The stippled vertical grey lines show the *MLS* for cod (44 cm), haddock (40 cm), and redfish (32 cm).

Effect of increasing mesh size on size selectivity

For cod, haddock, and redfish, the L50 values estimated for the 128 mm codend with both the standard and the shortened lastridge configuration were always lower than those for the 137 mm codend with the same configuration (Table 3). A comparison of the selectivity curves and the corresponding delta plots between the 128 mm and 137 mm codends in the standard configuration also illustrate the difference between the codends for all three species (Fig. 12). When the curves were compared for the codends in the standard configuration, the differences observed were significant for a few length classes that included fish above and below the *MLS* for haddock but only for fish above the *MLS* for cod and redfish (Fig. 12b, f, j). However, when the codends were compared in the shortened lastridge configuration, the differences between the codends increased substantially for all three species. Not only was the difference larger, but it was also significant for a larger number of length classes. For all three species, the 128 mm codend with shortened lastridge ropes captured significantly more fish of length classes both above and below the *MLS*, although the number of length classes that differed between the codends was substantially larger for cod and haddock than for redfish (Fig. 12d, h, l).

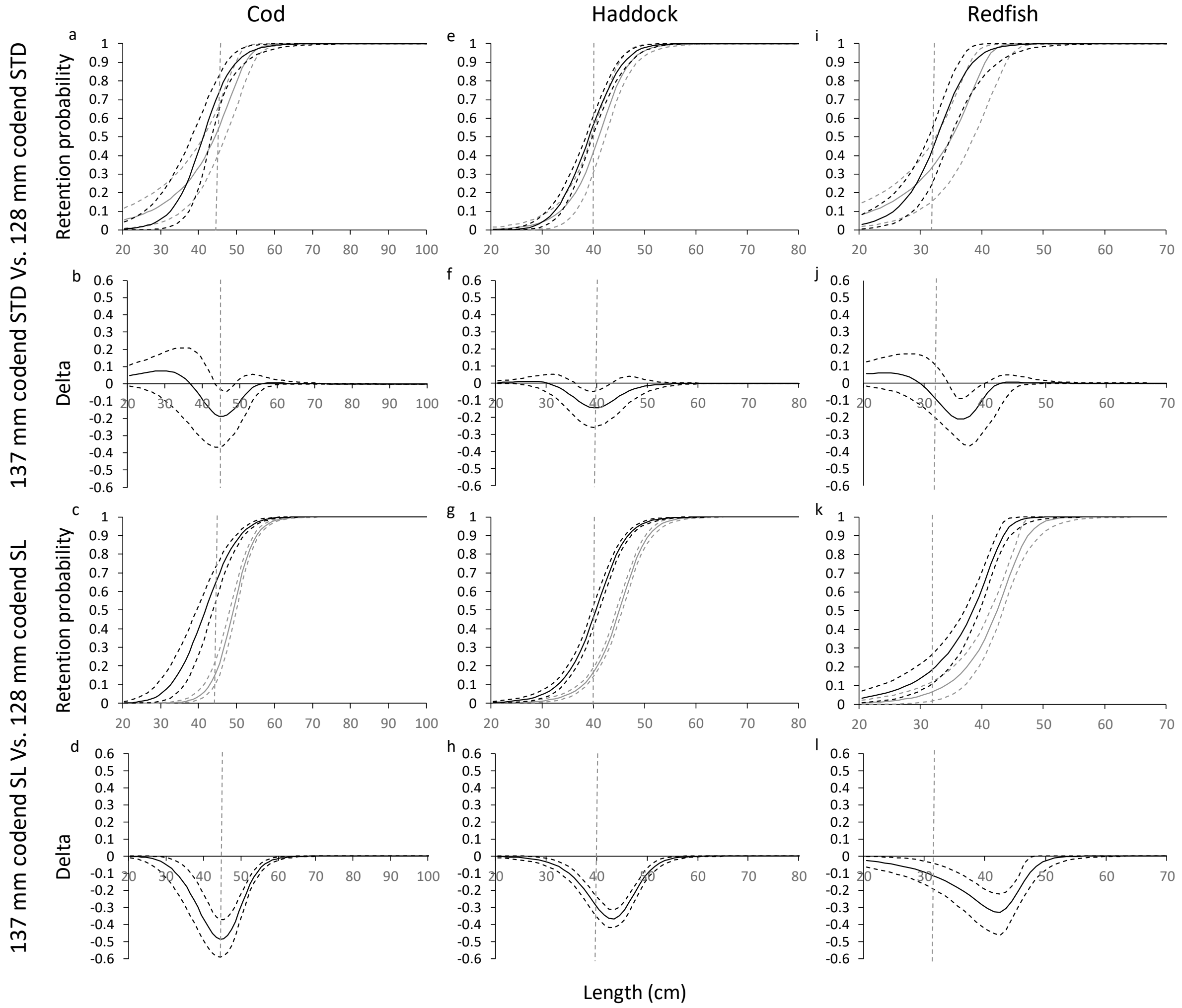


Figure 12: Comparison of the 128 mm (black) and 137 mm (grey) codends tested in both the standard and the short lastridge configurations. Delta plots of the comparisons are also shown. The stippled curves represent the 95% CIs in each case. The stippled vertical grey lines show the *MLS* for cod (44 cm), haddock (40 cm), and redfish (32 cm).

Effect of shortening lastridge ropes on size selectivity

The L50 values estimated for the two codends in the shortened lastridge rope configuration were always higher than the equivalent in the standard configuration (Table 3). A comparison of the selectivity curves and the corresponding delta plots obtained for cod, haddock, and redfish with the codends in the standard configuration and the shortened lastridge rope configuration showed that in general, shortening the lastridge ropes decreased the retention probability for the smaller length classes (Fig. 13). For the 128 mm codend, shortening the lastridge ropes resulted in no significant decrease in the retention probability of cod, a slight but significant decrease for some length classes of haddock, and a more considerable and significant effect on redfish (Fig. 13b, f, j). For the 137 mm codend, on the other hand, shortening the lastridge ropes led to a more pronounced reduction over a larger range of length classes for all three species (Fig. 13d, h, l). For this codend, the effect was largest for redfish and similar for cod and haddock.

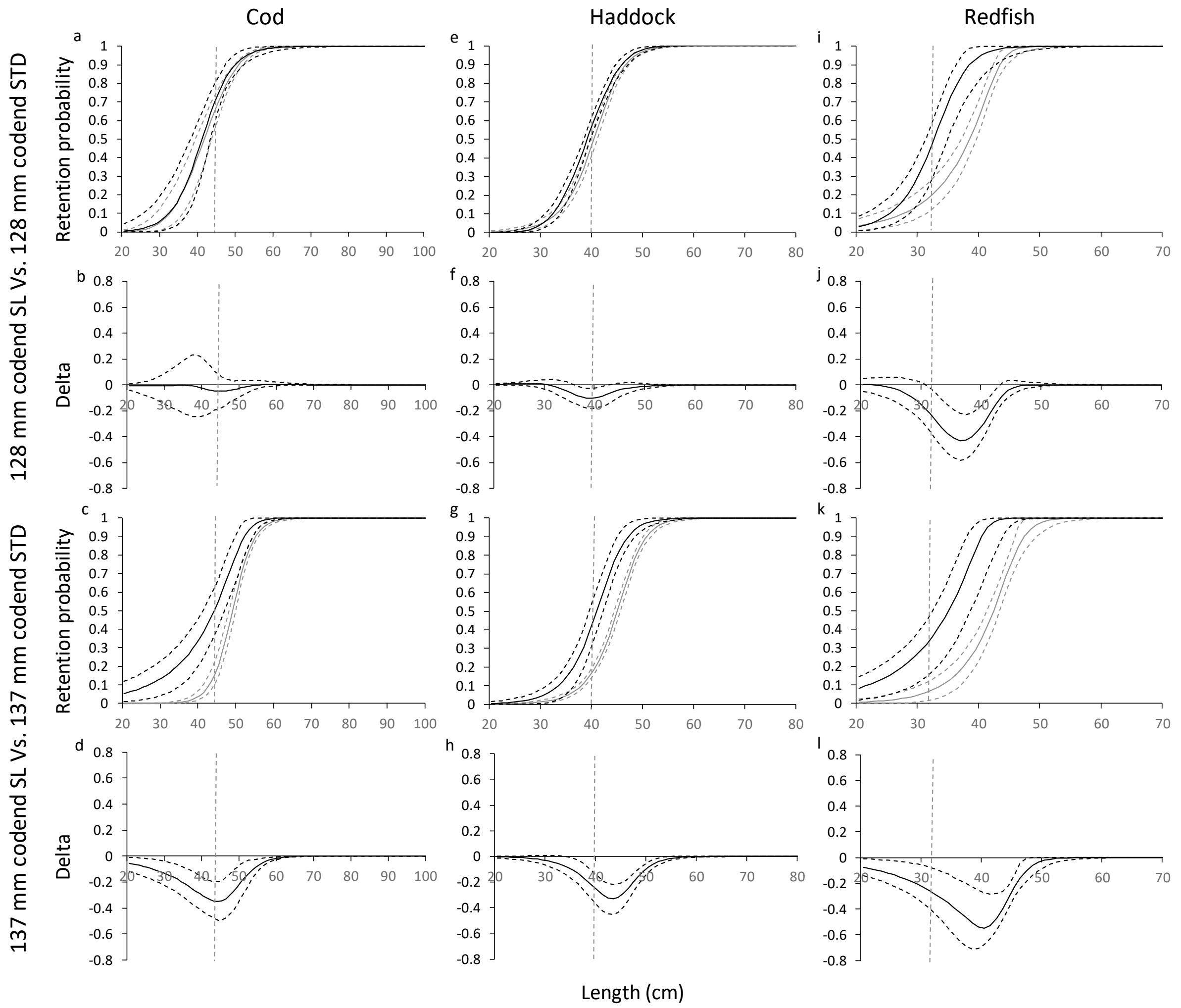


Figure 13: Comparison of the 128 mm and 137 mm codends in the standard configurations (black) and the configuration with shortened lastridge ropes. Delta plots of the comparisons are also shown. The stippled curves represent the 95% CIs in each case. The stippled vertical grey lines show the *MLS* for cod (44 cm), haddock (40 cm), and redfish (32 cm).

Simulation of the experimental selectivity curves and contribution of different meshes to size selectivity

The simulation results showed that for all four codend configurations and the three species included in the study, the experimental selectivity curves could be well explained by a combination of contributions from different mesh sizes and opening angles. In every case, the simulated selectivity curve was within the CIs of the experimental selectivity curves (Fig. 14). Further, the potential contributions of the different meshes and mesh openings showed that in general, cod, haddock, and especially redfish were able to utilize more open meshes or slack meshes to escape when the codends with short lastridge ropes were used (Table 4). This result indicates that with this configuration the longitudinal forces in the codend meshes were lower, providing greater availability of the more open meshes and slack meshes.

The simulations showed that when the 128 mm codend was employed, cod may have escaped through similar opening angles and mesh sizes independent of which gear configuration was used. For the 137 mm mesh codend, however, cod may have been able to use more of the larger meshes available and meshes with slightly higher opening angles when the shortened lastridge configuration was used in the codend (Table 4). The simulation results showed a similar pattern for haddock. However, the meshes with opening angles of 40–50° may have been more important for haddock than for cod, whereas meshes with opening angles of 20–30° showed higher relevance for cod (Table 4). Finally, the simulation of the results obtained experimentally for redfish showed that compared to cod and haddock, redfish potentially have greater ability to utilize meshes with higher opening angles or slack meshes that are deformable upon escape. Shortening the lastridge ropes likely allowed redfish to make use of meshes with higher opening angles and especially slack meshes. Finally, the simulations estimated that when the 128 mm and 137 mm codends were fished in the shortened lastridge configuration, 46.95% and 62.77%, respectively, of the redfish that escaped through the codend meshes may have done so through the largest meshes in the slack state available in the codend (Table 4). This result contrasts with that obtained for cod and haddock, which potentially did not use any slack meshes for escape. However, the use of slack meshes by redfish was the only explanation for the selectivity curve obtained for this species by simulation.

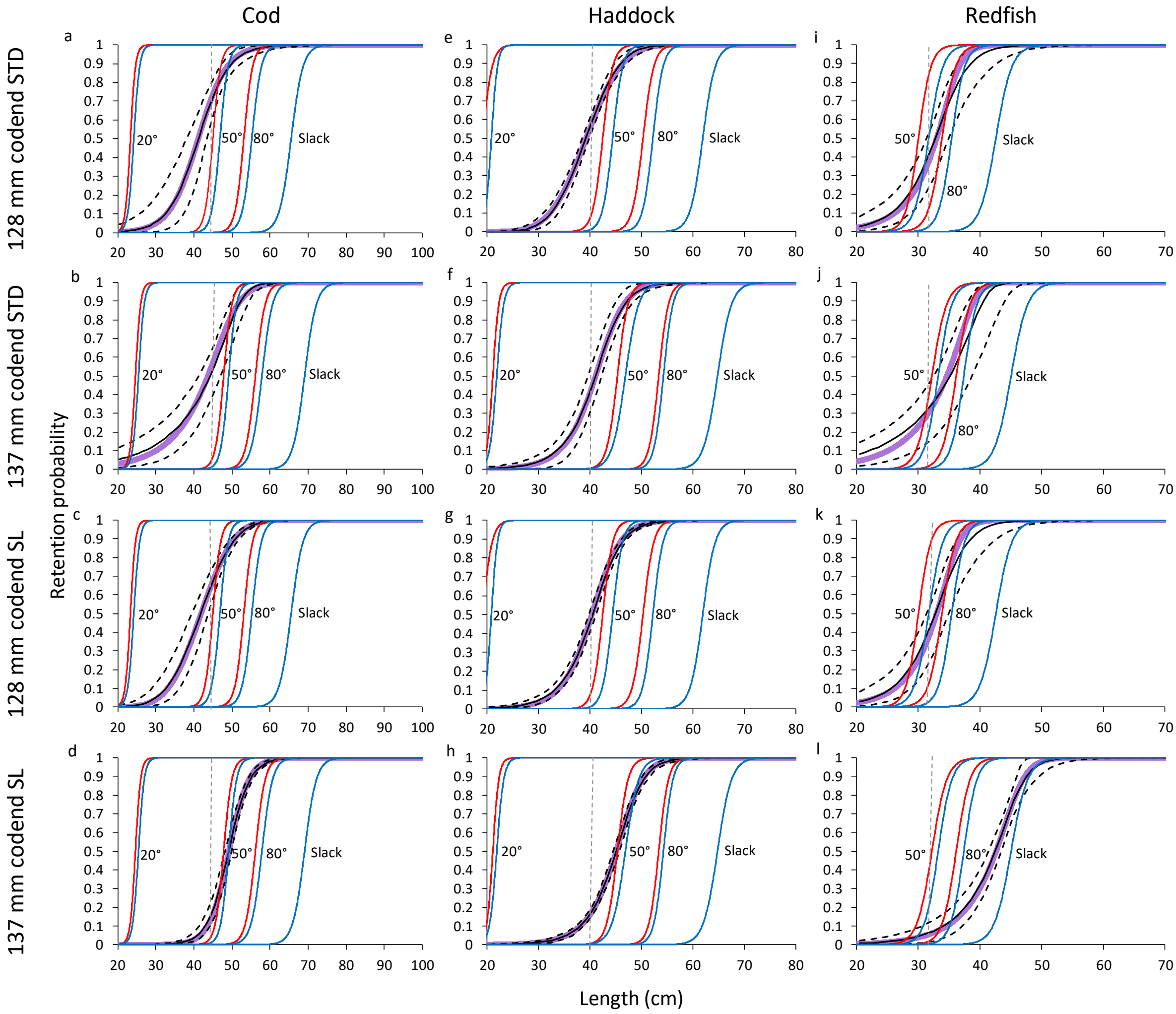


Figure 14: Experimental (black) and simulated (grey) size-selection curves for the four codend configurations tested during the trials. Stippled curves (black) show the 95% CIs. The red curves show selection curves simulated in FISHSELECT for meshes of 128 mm (a, c, e, g, i, and k) and 137 mm (b, d, f, h, j, and l) with opening angles of 20°, 50°, and 80°. The blue curves show selection curves simulated in FISHSELECT for meshes of 134 mm (a, c, e, g, i, and k) and 142 mm (b, d, f, h, j, and l) with opening angles of 20°, 50° and 80°. The blue line to the right in each plot shows the selection curve for a slack mesh of 134 mm (a, c, e, g, i, and k) and 142 mm (b, d, f, h, j, and l) in each case. The stippled vertical grey lines show the *MLS* for cod (44 cm), haddock (40 cm), and redfish (32 cm).

Table 4: Contribution (%) of the different codend mesh sizes, mesh opening angles (OAs), and mesh states considered as being potentially involved in reproducing experimental data for each of the four codends tested during the trials for cod, haddock, and redfish.

Cod								Haddock								Redfish							
128 mm codend				137 mm codend				128 mm codend				137 mm codend				128 mm codend				137 mm codend			
		STD	SL			STD	SL			STD	SL			STD	SL			STD	SL			STD	SL
Mesh size (mm)	OA			Mesh size (mm)	OA			Mesh size (mm)	OA			Mesh size (mm)	OA			Mesh size (mm)	OA			Mesh size (mm)	OA		
128	10°	*	*	137	10°	*	*	128	10°	*	*	137	10°	*	*	128	10°	*	*	137	10°	*	*
128	20°	*	*	137	20°	5.794	*	128	20°	*	*	137	20°	0.45	*	128	20°	*	*	137	20°	*	*
128	30°	9.394	7.812	137	30°	9.635	*	128	30°	4.636	2.420	137	30°	0.028	0.928	128	30°	3.25	*	137	30°	15.26	*
128	40°	18.789	17.135	137	40°	12.45	2.422	128	40°	25.78	20.773	137	40°	18.79	3.203	128	40°	9.704	9.828	137	40°	1.616	4.843
128	50°	17.363	14.640	137	50°	13.13	19.061	128	50°	23.95	28.100	137	50°	26.73	24.952	128	50°	18.91	0.001	137	50°	2.835	0.382
128	60°	1.919	4.549	137	60°	7.641	21.172	128	60°	2.089	1.184	137	60°	1.589	12.049	128	60°	5E-04	0.006	137	60°	6E-04	0.013
128	70°	0.284	0.692	137	70°	2.137	0.213	128	70°	1.092	2.207	137	70°	0.112	0.648	128	70°	0.004	0.002	137	70°	0.743	0.024
128	80°	0.001	0.081	137	80°	*	0.000	128	80°	*	*	137	80°	*	0.373	128	80°	1.072	0.003	137	80°	1.904	0.379
128	90°	*	0.001	137	90°	*	0.001	128	90°	*	*	137	90°	*	0.085	128	90°	0.009	0.000	137	90°	0.536	0.069
134	10°	*	*	142	10°	*	*	134	10°	*	*	142	10°	*	*	134	10°	*	*	142	10°	*	*
134	20°	*	*	142	20°	7.958	*	134	20°	*	*	142	20°	0.109	*	134	20°	*	*	142	20°	*	*
134	30°	18.086	16.743	142	30°	9.43	*	134	30°	5.32	4.671	142	30°	13.93	3.921	134	30°	3.676	*	142	30°	4.754	*
134	40°	16.938	16.099	142	40°	12.57	20.814	134	40°	20.86	19.950	142	40°	31.81	24.213	134	40°	5.827	6.097	142	40°	13.73	1.041
134	50°	7.556	12.620	142	50°	11.33	19.759	134	50°	9.345	14.186	142	50°	4.9	24.454	134	50°	1.747	0.002	142	50°	0.107	0.001
134	60°	1.656	1.299	142	60°	7.928	9.095	134	60°	6.924	6.507	142	60°	0.513	1.013	134	60°	0.002	0.007	142	60°	0.083	0.016
134	70°	2.925	3.127	142	70°	*	1.452	134	70°	*	*	142	70°	1.042	0.170	134	70°	26.93	3.646	142	70°	24.49	2.013
134	80°	5.091	5.201	142	80°	*	6.008	134	80°	*	*	142	80°	*	0.830	134	80°	26.87	23.173	142	80°	25.25	9.951
134	90°	*	*	142	90°	*	*	134	90°	*	*	142	90°	*	3.162	134	90°	1.989	10.279	142	90°	8.688	18.492
134	Slack	*	*	142	Slack	*	*	134	Slack	*	*	142	Slack	*	*	134	Slack	*	46.950	142	Slack	*	62.77

Exploitation pattern indicators for the four codend configurations tested

Exploitation pattern indicators depend on the fish population in the fishing area at the time of the trials. Therefore, to conduct a fair comparison between the different codends tested, the indicators for the four codend configurations tested during the trials were estimated based on the fish population encountered during the whole trial period (Fig. 15).

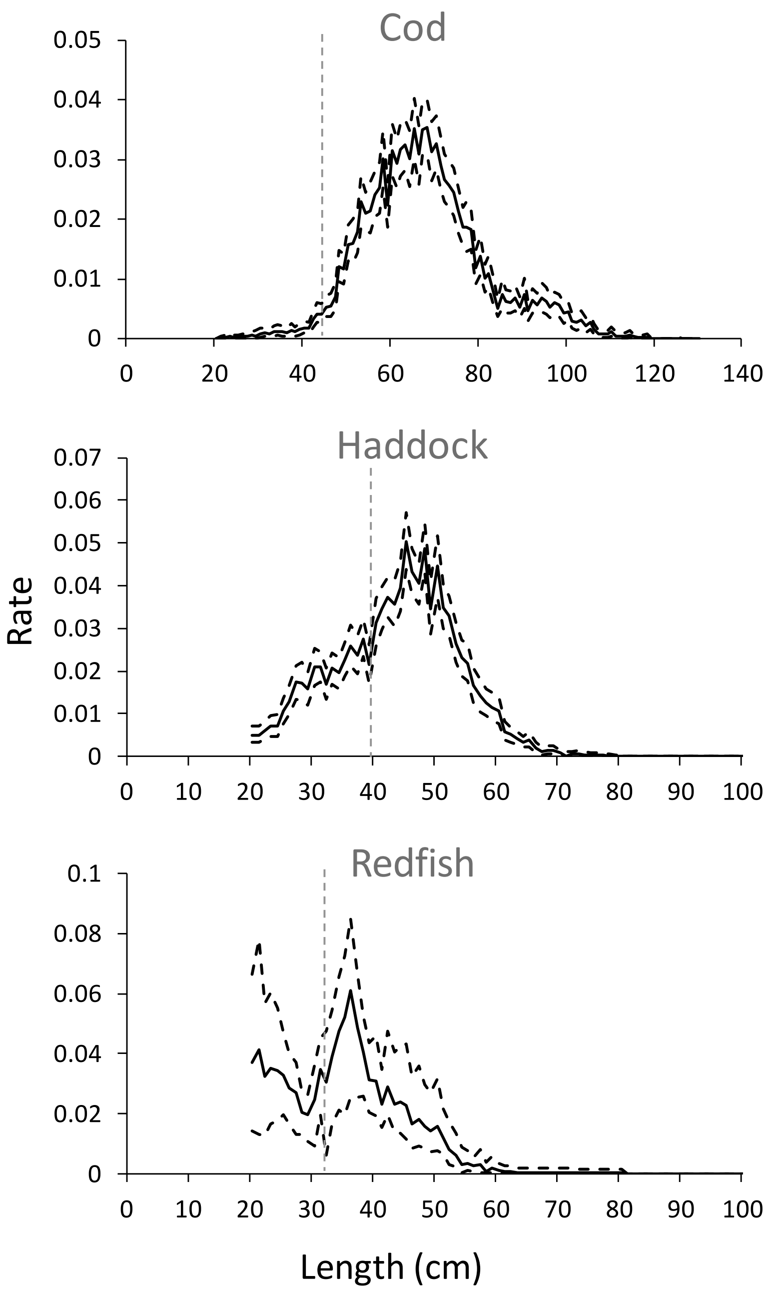


Figure 15: Size distribution of cod, haddock, and redfish populations encountered during the experimental trials.

For cod, the catch pattern indicators showed that the probability of catching fish under the *MLS* of 44 cm and the discard ratio decreased when we increased the mesh size from 128 mm to 137 mm, but the decrease was only statistically significant for the shortened lastridge rope configuration. When comparing the two gear configurations for the 128 mm codend, the gear change did not have a significant effect on either parameter. However, for the 137 mm codend, shortening the lastridge ropes significantly decreased the probability of capturing cod < 44 cm and the discard ratio, and the probability of retaining cod > 44 cm decreased from 97.4% to 94.1%. Increasing the *MLS* to 50 cm increased the probability of retaining cod both below and above the *MLS*. The discard ratio increased significantly for all four configurations (Table 5).

For haddock, as for cod, increasing mesh size in the standard codend configuration had no significant effect on any of the parameters estimated. The discard ratio only decreased from 8.7% to 6.7%, and although the probability of retaining fish < 40 cm decreased from 17.9% to 12.8%, the reduction was not statistically significant. However, all three indicators differed significantly when the codends were compared in the shortened lastridge configuration. As for cod, increasing the *MLS* from 40 mm to 45 mm significantly increased the retention probability for haddock above and below the *MLS* and the discard ratio for all four configurations tested. For example, the discard ratio for the 128 mm codend in the standard configuration increased from 8.7% to 28.1% when the *MLS* was increased from 40 cm to 45 cm.

For redfish, the probability of catching fish below or above *MLS* did not change significantly when the codend mesh size increased from 128 mm to 137 mm in either configuration. However, when we compared the two configurations with 128 mm or 137 mm codends, the probability of catching redfish below and above the *MLS* was substantially lower in the shortened lastridge configuration, and the reduction was statistically significant for the probability of catching redfish below the *MLS* for the 137 mm codend. The discard ratio did not differ significantly among any of the four codend configurations tested (Table 5).

Table 5: Exploitation pattern indicator values for the four codend configurations tested and the three species sampled during the sea trials. Indicator values for cod are shown for *MLS* of 44 cm and 50 cm. Indicator values for haddock are shown for *MLS* of 40 cm and 45 cm, indicator values for redfish are shown for *MLS* of 32 cm.

Cod

	Standard		Short lastridges			Standard		Short lastridges	
Indicator	128 mm	137 mm	128 mm	137 mm	Indicator	128 mm	137 mm	128 mm	137 mm
nP- 44 cm (%)	35.463 (22.132 - 50.274)	30.081 (18.114 - 41.813)	33.246 (22.725 - 43.973)	4.373 (2.452 - 7.305)	*nP*- 50 cm (%)	66.233 (57.821 - 74.074)	54.269 (41.362 - 65.610)	62.939 (55.087 - 70.401)	26.303 (20.191 - 32.951)
nP+ 44 cm (%)	98.331 (97.047 - 99.243)	97.369 (95.542 - 98.685)	98.141 (97.584 - 98.634)	94.064 (93.023 - 94.999)	*nP+* 50 cm (%)	99.096 (97.963 - 99.771)	98.845 (97.593 - 99.728)	99.086 (98.754 - 99.411)	96.808 (96.065 - 97.479)
$n_{Discard}$ (%)	0.894 (0.526 - 1.386)	0.767 (0.429 - 1.129)	0.840 (0.546 - 1.208)	0.116 (0.063 - 0.194)	$n_{Discard}$ (%)	4.788 (4.052 - 5.754)	3.967 (3.001 - 4.903)	4.561 (3.813 - 5.365)	2.003 (1.527 - 2.529)

Haddock

	Standard		Short lastridges			Standard		Short lastridges	
Indicator	128 mm	137 mm	128 mm	137 mm	Indicator	128 mm	137 mm	128 mm	137 mm
nP- 40 cm (%)	17.880 (14.074 - 22.034)	12.804 (6.602 - 17.974)	14.220 (11.703 - 17.386)	4.406 (3.203 - 5.722)	*nP*- 45 cm (%)	37.498 (33.899 - 41.692)	30.284 (23.674 - 36.990)	32.611 (29.348 - 36.712)	13.889 (12.120 - 15.853)
nP+ 40 cm (%)	90.551 (88.109 - 92.902)	86.188 (82.030 - 91.200)	87.762 (85.712 - 89.825)	70.030 (67.061 - 72.930)	*nP+* 45 cm (%)	96.751 (94.907 - 98.265)	94.803 (92.007 - 98.254)	95.514 (94.495 - 96.491)	83.943 (81.393 - 86.155)
$n_{Discard}$ (%)	8.659 (6.738 - 10.458)	6.657 (3.559 - 9.086)	7.218 (5.855 - 8.765)	2.932 (2.105 - 3.850)	$n_{Discard}$ (%)	28.130 (25.180 - 31.074)	24.392 (19.944 - 28.677)	25.640 (22.628 - 28.546)	14.318 (12.373 - 16.416)

Redfish

	Standard		Short lastridges	
Indicator	128 mm	137 mm	128 mm	137 mm
nP- 32 cm (%)	13.779 (5.716 - 22.914)	16.817 (5.868 - 25.720)	8.105 (3.455 - 14.087)	2.338 (0.311 - 5.407)
nP+ 32 cm (%)	85.352 (71.979 - 94.449)	75.440 (56.707 - 89.826)	60.400 (50.563 - 75.591)	41.271 (30.162 - 57.885)
$n_{Discard}$ (%)	8.596 (3.726 - 14.147)	11.493 (4.408 - 17.719)	7.250 (2.894 - 12.091)	3.194 (0.400 - 7.083)

Comparison of the exploitation pattern indicators of the four codend configurations tested with those of the gear currently used in the fishery

The exploitation pattern indicators for the Sort-V and Flexigrid grid systems combined with a diamond mesh codend (Table 6) showed that the probability of retaining fish under the *MLS* was low (< 5% for cod, < 1% for haddock, and < 1% for redfish). Increasing the *MLS* to 50 cm for cod and 45 cm for haddock increased the probability of catching undersized cod to ca. 15% and < 3% for haddock. These increases were significant in both cases. The results also showed that while the retention probabilities for cod with the Sort-V grid and Flexigrid were over 87% and 83%, respectively, regardless of the *MLS* used, for haddock the retention probability with the grid systems could be as low as 24% and not higher than 47% (Table 6). With increasing *MLS*, the discard ratio increased by approximately 1% for cod for both grids and approximately 4% for haddock with the Sort-V grid and 130 mm codend, and the increase was statistically significant in both cases (Table 6). The retention probability for undersized redfish and the discard ratio with the Sort-V grid and codend system were low, but the retention probability for fish above the *MLS* was also low and under 30% (Table 6).

The probability of retaining fish above the *MLS* and the discard ratio are two important indicators to consider when comparing the performance of different gear, as the former is a measure of the efficiency of the gear and the latter is a measure of the undersized fish caught with respect to the number of fish above the *MLS* caught. We used these two indicators to compare the performance of the four codend configurations tested in the present study with that of the Sort-V and Flexigrid grid sections combined with a 130 mm codend (Fig. 15).

Considering the current *MLS* for cod in the Barents Sea, the retention probability of commercial fish for all four codend configurations tested in this study was > 94% in all cases, whereas retention probability was 87% and 83% for the Sort-V grid and Flexigrid systems, respectively. If the *MLS* was increased to 50 cm for cod, the retention probability for all four codend configurations tested would be > 96%, whereas it would be 90% and 86% for the Sort-V grid and Flexigrid systems, respectively (Tables 5–6). Regardless of the *MLS* considered, the retention probability for cod with the four codend configurations tested was significantly higher than that for the two grid configurations (Fig. 15). The discard ratio for cod was < 1% for all six configurations when the *MLS* was 44 cm and < 5% when the *MLS* was increased to 50 cm. Although the discard ratio differences were not large, they were significant among all codend configurations tested except the 137 mm codend with shortened lastridge ropes and the Sort-V grid and Flexigrid systems (Tables 5–6, Fig. 15).

At the *MLS* of 40 cm, the retention probability for haddock for the four codend configurations tested varied between 70% and 91%, whereas the values were 36% to 24% for the Sort-V and Flexigrid systems, respectively (Tables 5–6). The difference between the four codend configurations and the grids was significant (Fig. 15). Increasing the *MLS* to 45 cm increased the retention probability of haddock in all cases, with estimated values of 85–97% for the four codend configurations tested, 47% for the Sort-V system, and 31% for the Flexigrid system (Tables 5–6). The difference between all four codends and the two grid systems was still statistically significant (Fig. 15). However, the discard ratio was significantly higher for the test codends than for the two grid systems in every case, regardless of the *MLS* considered. At the *MLS* of 40 cm, the discard ratio for the test codends never exceeded 9%, but increasing the *MLS* to 45 cm resulted in a 28% discard ratio for the 128 mm codend in the standard configuration (Tables 5–6, Fig. 15).

The retention probability for redfish > 32 cm was significantly higher for all codend configurations compared to the Sort-V system, except for the 137 mm codend with shortened lastridge ropes. The discard ratio was substantially lower with the Sort-V grid than with all codend configurations except for the 137 mm codend with shortened lastridge ropes. However, the difference was not statistically significant in any of the cases (Fig. 15).

Table 6: Exploitation pattern indicator values obtained for two grid and codend gear configurations used in the fishery today. Note that the minimum mesh size in the codend, which was 135 mm in 2010, is now 130 mm. The selectivity data for the estimation of the indicators are based on the data presented in Sistiaga et al. (2010), Herrmann et al. (2012), and Brinkhof et al. (2020). The populations used for all three species are those shown in Figure 15. Indicator values for cod are shown for *MLS* of 44 cm and 50 cm. Indicator values for haddock are shown for *MLS* of 40 cm and 45 cm. Indicator values for redfish are shown for *MLS* of 32 cm.

Cod

Indicator	Sort-V + Codend	Flexigrid + Codend	Indicator	Sort-V + Codend	Flexigrid + Codend
$nP-$ 44 cm (%)	4.555 (2.793 - 7.422)	3.672 (1.705 - 7.009)	$nP-$ 50 cm (%)	15.962 (12.465 - 20.359)	14.868 (9.682 - 20.634)
$nP+$ 44 cm (%)	87.240 (84.531 - 89.439)	83.059 (78.950 - 86.194)	$nP+$ 50 cm (%)	90.433 (87.930 - 92.421)	86.106 (82.108 - 89.140)
n_{Discard} (%)	0.130 (0.077 - 0.222)	0.110 (0.051 - 0.215)	n_{Discard} (%)	1.311 (1.004 - 1.659)	1.282 (0.861 - 1.747)

Haddock

Indicator	Sort-V + Codend	Flexigrid + Codend	Indicator	Sort-V + Codend	Flexigrid + Codend
$nP-$ 40 cm (%)	0.504 (0.242 - 0.863)	0.203 (0.051 - 0.461)	$nP-$ 45 cm (%)	2.185 (1.458 - 3.017)	0.854 (0.363 - 1.555)
$nP+$ 40 cm (%)	35.904 (31.288 - 40.007)	23.73 (20.345 - 27.693)	$nP+$ 45 cm (%)	46.878 (41.398 - 51.671)	31.494 (27.154 - 36.161)
n_{Discard} (%)	0.669 (0.338 - 1.152)	0.409 (0.096 - 0.914)	n_{Discard} (%)	4.495 (3.212 - 6.108)	2.664 (1.139 - 4.683)

Redfish

Indicator	Sort-V + Codend
$nP-$ 32 cm (%)	0.121 (0.007 - 2.595)
$nP+$ 32 cm (%)	29.081 (20.039 - 45.039)
n_{Discard} (%)	0.243 (0.015 - 4.682)

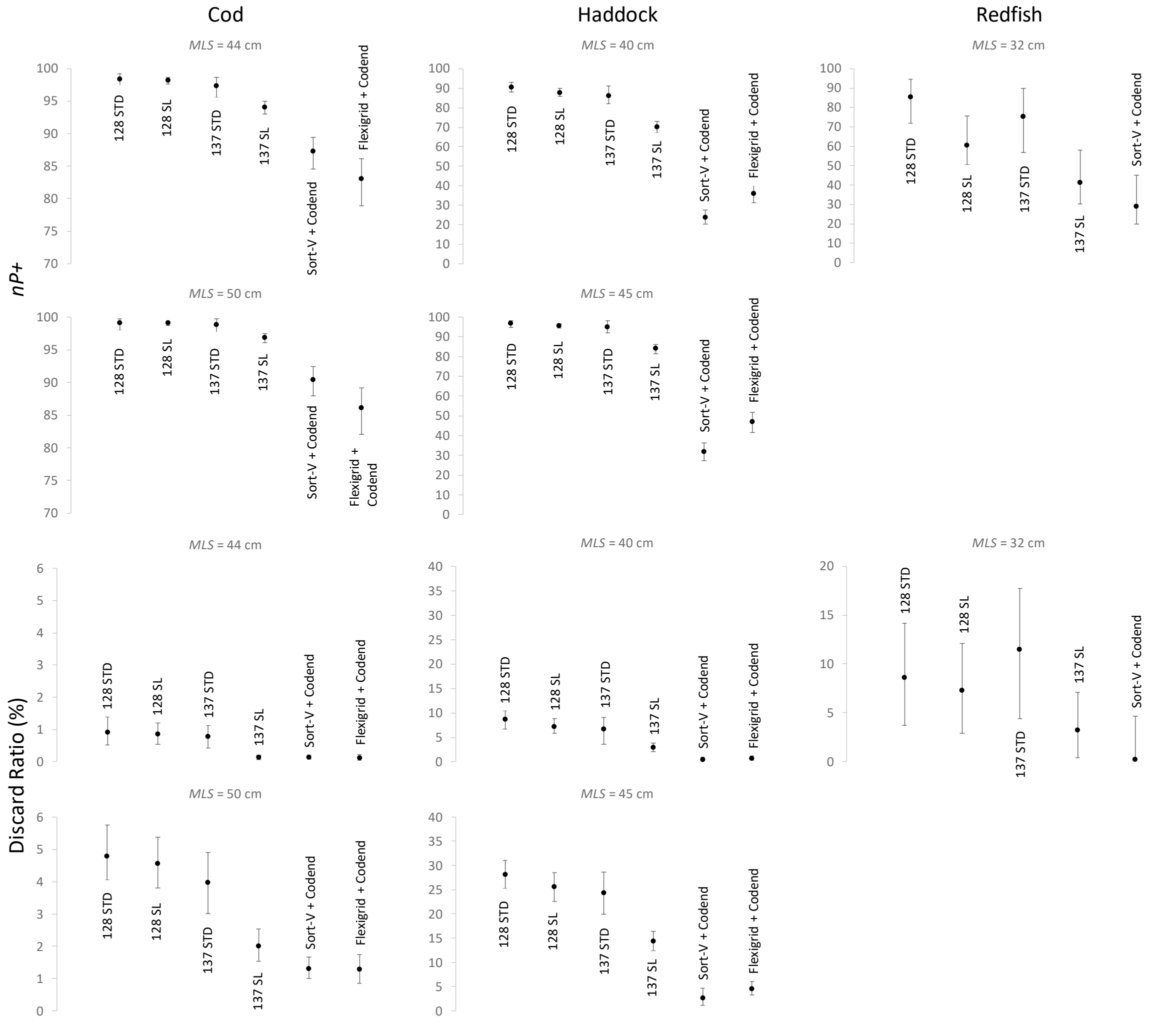


Figure 15: Values for the indicators *nP*+ and discard ratio (%) for cod for *MLS* of 44 cm and 50 cm, for haddock for *MLS* of 40 cm and 45 cm, and for redfish for 32 cm (Tables 5–6) for the four codends tested in this study and the two grid systems used today in the Barents Sea bottom trawl gadoid fishery.

3.1.5. Discussion

In this study, we compared catch results for two diamond mesh codends with different mesh sizes in a standard and a shortened lastridge configuration. Both increasing mesh size from 128 to 137 mm and shortening the lastridge ropes for both codends so that they were 15% shorter than the stretched codend netting significantly changed the selection properties of the codend for cod, haddock, and redfish (Figs. 12–13). The effect of mesh size was a consequence of the fact that physically larger fish are able to penetrate larger meshes. The selectivity changes caused by shortening the lastridge ropes occurred because this modification removes the tension from the netting generated by the accumulation of fish inside the codend, which results in slacker and more open meshes (Herrmann 2005a, b). The effect on selectivity of increasing mesh size was more pronounced for the codends in the shortened lastridge configuration than in the standard configuration. Because shortening lastridge ropes contributes to more slack meshes with higher opening angles in the codend, we expected a larger effect of changing codend mesh size on size selection with this configuration compared to the standard configuration. The effect on the size-selection properties of the diamond mesh in the shortened lastridge configuration was clear for both codends, but it was more pronounced for the 137 mm codend. This difference likely was due to the stiff netting material used, which could have reduced the effect of the shortened lastridge ropes for the smaller mesh size.

The simulation carried out using the existing FISHSELECT models for cod, haddock, and redfish (Sistiaga et al. 2011; Herrmann et al. 2012) showed that it is indeed possible to explain the selectivity results obtained for these three species and the four diamond mesh codend configurations tested in our study. The results indicate that when using shortened lastridge codends, the availability of meshes with high opening angles is larger and all three species investigated are able to escape through these meshes. The largest contributions were for mesh opening angles of 40–60° for cod and haddock and 80–90° for redfish. It is unclear why the largest contribution to size selectivity for redfish changed from nearly square meshes when using the standard configuration to slack meshes when using the short lastridge configuration. Redfish is a robust fish that tries so hard to squeeze itself through meshes that it often gets stuck (Isaksen and Valdemarsen 1986; ICES 2012). However, considering the stiffness of the material used in the codends (single braided polyethylene hotmelt twine, Ø8 mm), it is difficult to understand how the meshes could be slack enough to deform and allow redfish to pass through them. The experimental design and data analysis in this study do not allow us to provide a clear explanation for the observed redfish selectivity results other than those already discussed.

In recent years, the use of exploitation pattern indicators has gained popularity in size selectivity studies (Santos et al. 2016; Sala et al. 2017; Cheng et al. 2019; Kalogirou et al. 2019; Melli et al. 2020) because they provide a good picture of how the gear performs with respect to the management objectives and alternative catch pattern objectives in the fishery. Considering the *MLS* for cod, haddock, and redfish, the estimated indicator values showed that the tested codend configurations performed quite differently. While the 137 mm codend with shortened lastridge ropes retained < 5% of undersized fish of all three species and > 94% of the cod above *MLS*, it resulted in a loss of ~30% and ~60% of commercial haddock and redfish, respectively. On the other hand, reducing the mesh size to 128 mm for the same codend configuration reduced the loss of commercial haddock and redfish to 13% and 40%, respectively, but the catch of undersized cod with this codend configuration increased to over 30%. The indicator results obtained with the 137 mm shortened lastridge codend fit with the goals of the fleet of keeping haddock and cod larger than 45 cm and 50 cm, respectively, whereas using the 128 mm codend captured lower value haddock and cod. However, the shortened lastridge 137 mm codend that caught < 5% of cod below the *MLS* also caught over 25% of fish below 50 cm. Overall, these indicator results illustrate the challenge of multispecies fisheries and the difficulty of finding optimal gear solutions that provide satisfactory and efficient results for different species simultaneously. Our results also show that a change of 5 or 6 cm in the legal or desired minimum size of a certain species can notably change the performance of the gear with respect to this new potential goal. However, we must stress that the indicators depend on the specific population the gear encounters for each species during the trials and that selectivity estimates can provide a more general picture of the selective performance of the gear tested.

Compared to the mandatory sorting grid and codend gear used in the Barents Sea gadoid fishery, all codend configurations tested in this study retained significantly more commercial-sized cod and had a discard ratio that was only marginally larger. The pattern was similar when the minimum size was for cod was set at 50 cm, but in this case the retention of commercial cod was substantially larger and the discard ratio was always < 5%. From this perspective, the diamond mesh codends, and especially the 137 mm codend, with shortened lastridge ropes resulted in more satisfactory selection than the grid and codend configurations used in the fishery today. The patterns observed for haddock were similar to those for cod, although for this species the differences between the grid systems and the codends tested in the present study were more pronounced. It is clear from the results that removing the grids from the fishery would significantly increase the retention of haddock over the current *MLS* and haddock above 45 cm. However, the discard ratio for the codends tested was much larger than for the grid and codend configurations. For three of the four codends tested when the *MLS* was set at 45 cm, 25% of the catch would be below this size. Only the 137 mm codend with shortened lastridge ropes was able to keep the discard ratio for haddock below 15%. For redfish, the differences between the Sort-V grid system and the tested codends were similar to but not as clear as those for cod and haddock, so it is more difficult to draw a conclusion about the extent to which the fishery would benefit from removing the grids and using any of the different types of codends tested in this study.

In general, the indicator results obtained and our comparison of the performance of the compulsory grid systems used in the Barents Sea today with the codends tested in our study showed that in many cases shortened lastridge codends can provide a better catch pattern than the grid system for the species of interest. Particularly for cod, and to a large extent for haddock, the 137 mm codend with shortened lastridge ropes resulted in a significantly higher retention of fish above the *MLS* with an insignificant or small increase in the discard ratio compared to the compulsory grid system. Therefore, in terms of size selection, our results show that a codend with shortened lastridge ropes is an alternative to the grid and codend gear currently required in the Barents Sea demersal trawl fishery.

Despite the positive selectivity results obtained with the codends in the shortened lastridge configuration and their maneuverability and encouraging performance compared to the grid systems, other aspects need to be considered. For example, it is important to understand how and when fish escape through the selection device. Selectivity through codend meshes is highly dependent on fish behavior, meaning that fish must actively swim through the meshes to escape. While species such as haddock are active in the gear, species like cod are often more dependent on additional stimuli to attempt escape (Tschernij and Suuronen 2002; Grimaldo et al. 2018). Decompression experienced during haul back can be an additional escape stimulus (Madsen et al. 2008; Grimaldo et al. 2009; Grimaldo et al. 2014), but it creates additional risk of injury and potentially reduced survival for the escapees (Breen et al. 2007). Earlier studies reported that contrary to the selectivity of codends, grid selectivity is a more mechanical size-selection process that takes place at the fishing depth (Grimaldo et al. 2009). This argument is often used by the management authorities in the Barents Sea to maintain the grid and codend configuration that is compulsory in the area today. Whether the properties of codends with shortened lastridge ropes are different from ordinary codends in this respect is unknown and should be investigated, as the availability of more open meshes in the codend may stimulate fish to escape earlier in the capture process.

Selectivity gears based on netting meshes can lose their selection properties over time. Square-meshed panels (e.g., the BACOMA codend (Herrmann et al. 2015; Madsen et al. 2015), codends with lateral exit windows (Grimaldo et al. 2008; Grimaldo et al. 2009), and T90 codends (ICES 2011; Madsen et al. 2015; Cheng et al. 2020)) have good selection properties for cod and haddock. However, deformation of the meshes and loss of stiffness over time may change the selection properties of these types of codends. Likewise, codends with lastridge ropes can potentially lose their properties over time. Ropes, especially twisted ropes, stretch with use, and this property depends on rope construction and material (McKenna et al. 2004). If ropes increase in length, the effect of shortened lastridge ropes would be reduced over time and the meshes in the codend would close. If ropes stretch, the crew may have to adjust them repeatedly to avoid losing the selective properties of the gear and comply with regulations. A potential solution to avoid stretching is the use of Dyneema ropes, which in principle stretch little (< 3.5%) (Thomas and Lekshmi 2017). However, Dyneema ropes have little load absorption due to their limited stretchability. Thus, material selection is a key to designing appropriate lastridge ropes, and further research of the quality and performance over time of different types of lastridge ropes is necessary.

Considering the results obtained in earlier trials (Isaksen and Valdemarsen 1990; Lök et al. 1997; Ingolfsson and Brinkhof 2020) and the results from our study, we conclude that codends with shortened lastridge ropes are satisfactory selection devices that could be used in the Barents Sea gadoid fishery and other fisheries to replace or supplement other sorting devices. However, selection during the capture process and the properties and performance of different types of lastridge ropes over time require further investigation.

4. Cruise February/March 2021 onboard R/V Helmer Hanssen

4.1. Short lastridge rope codend vs Sort-V sorting grid

4.1.1. Summary

The compulsory configuration comprising of a rigid sorting grid followed by a diamond meshed codend in the Northeast Atlantic bottom trawl fishery for gadoids has caused some additional challenges. This study investigated the size selectivity and catch efficiency for cod (*Gadus morhus*) and haddock (*Melanogrammus aeglefinus*) in a codend with shortened lastridge ropes in comparison with the compulsory configuration. The size selectivity results

demonstrated that the configuration with the short lastridge codend caught significantly more cod and haddock both below and above the minimum reference size (MRL). Specifically, the catch pattern indicators demonstrated that the configuration with the short lastridge codend retained 5.9% more cod above MRL, an increase that was significant, while the difference below MRL was not significant. For haddock, the codend with short lastridges retained 6.1% more fish below MRL, and 45% more fish above the MRL compared to the configuration with the Sort-V with regular codend.

4.1.2. Introduction

Northeast Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) are the two most important species in the Barents Sea demersal trawl fishery in terms of value and quantity (Yaragina et al., 2011). For 2020 the ICES advised a quota of 689 672 metric tons for cod, and 215 000 for haddock, which is equally divided between Norway and Russia (ICES, 2019). The fishery is regulated amongst others with a general discard ban and minimum reference size of 44 cm for cod and 40 cm for haddock. Catches can contain a maximum of 15 % of fish below the MRL, and if exceeded the areas become temporarily closed for fishing (Ministry of Trade, Industry and Fisheries, 2020). Specifically, for the demersal trawl fishery the regulation comprises amongst others of compulsory use of a selective grid with 55 mm bar spacing followed by a codend with a minimum mesh size of 130 mm. The size selective sorting grids were developed during the early 1990 and became mandatory in 1997. Out of the three different sorting grids that are allowed to use, the Sort-X, Sort-V and Flexigrid, only the two latter ones are currently used by the fishing fleet (Grimaldo et al., 2015; Sistiaga et al., 2016, Brinkhof et al., 2020).

In general, the size selective sorting grids have had a significant contribution to the fisheries sustainability by reducing the catch of fish below the MRL. However, several recent studies have documented that the size selective properties of the grids can vary under different circumstances (Sistiaga et al., 2016). Besides releasing most of the fish below MRL, also large proportions of fish above MRL are released by the grids (Brinkhof et al., 2020). This is especially the case for haddock which has a lower MRL than cod even though both species are mostly caught simultaneously (Brinkhof et al., 2020). Furthermore, the grids reduce the water flow inside the section causing blockage of fish especially under circumstances with high entry rates. Consequently, this causes a risk of excessively large catches since the fish does not fall back into the codend and is thus not registered by the catch sensors, subsequently causing a risk of gear damage and loss of catch (Grimaldo et al., 2014; Sistiaga et al., 2016).

The size selective grids were developed as a consequence of the unsatisfactory selectivity results in the diamond meshed codend applied. Poor size selectivity in diamond meshed codends have been reported by several studies (Robertson and Stewart, 1988; Herrmann, 2005a,b; Sala et al., 2008; Wienbeck, 2011). One of the major challenges with regular diamond meshed codend is the closing of the meshes when the catch accumulates in the aft of the codend, consequently confining satisfactory selectivity. However, improved size selectivity can be achieved without adding additional sorting devices by making simple modifications to the netting in the codend. Several recent studies from the Barents Sea demersal trawl fishery have focused on solving this issue by removing the sorting grid and investigating different mesh configurations in the codend, such as exit windows, T90 (turning the orientation of the meshes 90 degrees perpendicular to the towing direction), and shortened lastridge ropes (Jørgensen and Ingolfsson, 2006; Grimaldo et al., 2008; Grimaldo et al., 2018; Ingolfsson and Brinkhof, 2020; Brinkhof et al., 2021 (unpublished)). Codends with T90-netting or shortened lastridge ropes have in common that the meshes remain open regardless of the accumulating catch during towing. Ingolfsson and Brinkhof (2020) tested a configuration without a grid and replacing the regular codend with a knotless, 4-panel codend with short lastridges with a mesh size of 155 mm. The codend did barely retain any fish below MRL, however, due to the large mesh size it also released large proportions of fish above MRL. Therefore, it would be of interested to test a similar codend with a lower mesh size in direct comparison with a sorting grid. Hence, this study will focus on the following research questions:

- What is the size selectivity and catch efficiency of cod, haddock with the legislated configuration comprising of the Sort-V grid and a regular diamond mesh codend?
- What is the size selectivity and catch efficiency when removing the Sort-V grid and substituting the regular diamond meshed codend with a four-panel knotless codend with short lastridge ropes?
- What is the size selectivity and catch efficiency for the regular diamond meshed codend alone?
- Is there any difference in size selectivity and catch efficiency between these configurations?

4.1.3. Materials and methods

Fishing trials

Experimental fishing was conducted in the southern Barents Sea from 19th to 28th of February 2021 onboard R/V "Helmer Hanssen". Two identical Alfredo 3 trawls were towed alternately. The trawls were towed with a set of Injector Scorpion otter boards (weighing 3100 kg, with an area of 8m^2 each). The otter boards were connected to 60 m long sweeps with 3 m long backstraps followed by 7 m long connector wire. A Ø53 cm steel bobbin was inserted in the middle of the sweeps to protect the sweeps from excessive abrasion. The sweeps were connected to the 46 m long ground gear which comprised of 18.9 m long rock-hopper gear (Ø53 cm) in the middle followed by a 14 m long (Ø 19 mm) chain with three equally spaced steel bobbins (Ø53 cm). The rock hopper gear was attached to the 19.2m long fishing line. The headline of the trawls was 36.5 m long. The trawls itself were two-panels trawls, 420 meshes in circumference and built entirely of polyethylene (PE) netting with 155 mm mesh size.

One trawl was rigged similar as in the commercial fishery. The trawl belly was followed by a section with a Sort-V grid (dimensions…) with a bar spacing of 54.8 ± 1.1 mm (mean ± SD). An extension piece was inserted between the grid section and the codend. The codend itself was a two-panel codend, 12 m long and 60 meshes in circumference. The codend was built of single braided Ø8 mm hotmelt PE twine (Polar Gold), with a mesh size of 133.8 ± 2.2 mm (mean ± SD), and thus similar to that commonly used in the commercial fishery. To catch the escapees from the grid a cover was mounted over the escape outlet. The cover had an inner mesh size of 45.8 ± 1.5 mm (mean ± SD) covered with a large mesh netting on the outside to ensure sufficient strength and was equipped with seven floats to avoid blockage of the outlet (Fig. 16). To catch the codend escapees the entire length of the codend was covered with a cover. To ensure that the cover stayed clear from the codend itself the front part of the cover was equipped with six floats, three kites, and a 12 kg piece of chain on the top, side and bottom part of the codend, respectively. Also, twelve kites were attached to the cover around the bulk of the catch in the codend (Fig. 16). The cover had a mesh size of 51 ± 1.3 mm (mean ± SD) and was strengthened with an outer layer of large meshed netting in the aft.

The other trawl was equipped with an extension piece substituting the grid section. This section was followed by 2 to 4 panel transition piece which was mounted to the codend (Fig. 16). The codend itself was a 4-panel (4 x 15 meshes in circumference) codend built of knotless braided Ø 6 mm PE (Euroline). The codend had a mesh size of 131 ± 1.3 mm (mean ± SD). To catch the escapees the entire length of the codend was covered with a cover. The cover was identical to the one used on the other trawl and had a mesh size 41 ± 1.1 mm (mean ± SD). All mesh and bar spacing mesurements were conducted applying an OMEGA gauage and followed the procedure described in Wileman et al. (1996).

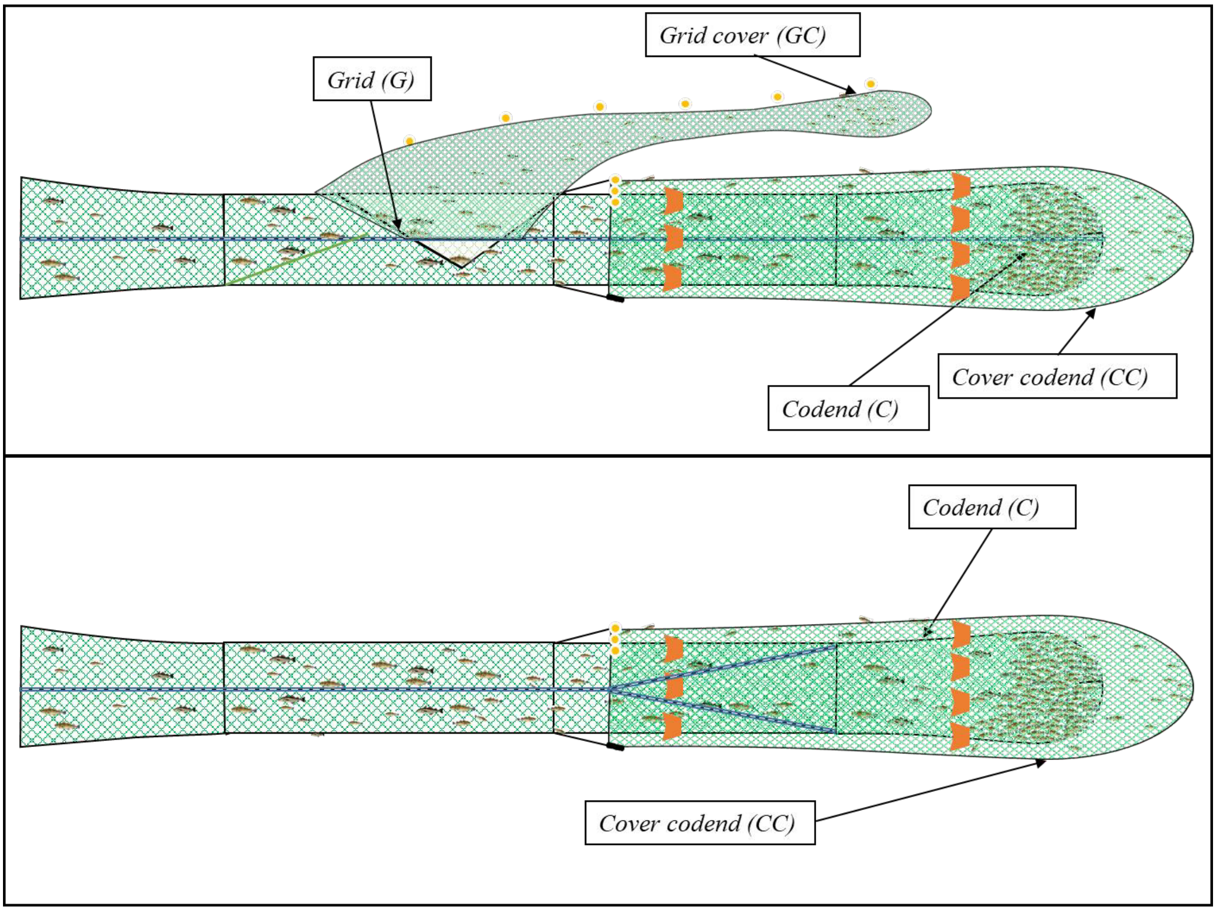


Figure 16. Illustration showing the experimental design employed during the trials. Above, the conventional configuration with the Sort-V grid (*G*) and the 130 mm diamond meshed codend (*C*) with the covers covering the grid (*GC*), and codend (*CC*). Below, the experimental design applied for the trawl with the codend with shortened lastridged (*C*), with the covered codend (*CC*).

The trawl performance was monitored continuously applying a set of trawl door sensors, a trawl height, and a catch volume sensor from Scanmar. The catch in each compartment was kept apart in separate holding bins. The length of all cod and haddock above 20 cm was measured to the nearest centimeter below.

Statistical analysis

Modeling and estimation of the size selection in the codend with shortened lastridged

Analysis of each species was done separately using the same method described hereafter. The applied experimental design (Fig. 16) for the test of the codend with shortened lastridged enabled analysis of the collected catch data as binominal data, where individuals, either retained by the codend cover or by the codend itself, are used to estimate the size selection in the codend (i.e., length-dependent retention probability). Between hauls with the same codend, the size selectivity is expected to vary (Fryer, 1991). In this study, we were interested in the size selection averaged over hauls, since this would provide information about the average consequences for the size selection process when applying the codend in the fishery. We tested different parametric models $r_{codend}(l, \boldsymbol{v_{codend}})$ for the codend size selection. $\boldsymbol{v_{codend}}$ is a vector consisting of the parameters of the model. The purpose of the analysis is to estimate the values of the parameter $\boldsymbol{v_{codend}}$ that make experimental data (averaged over hauls) most likely to be observed. For this purpose, the following expression was minimized which corresponds to maximize the likelihood for the observed experimental data:

$$-\sum_{j=1}^{m}\sum_{l}\{nC_{lj} \times ln(r_{codend}(l, \boldsymbol{v_{codend}})) + nCC_{lj} \times ln(1.0 - r_{codend}(l, \boldsymbol{v_{codend}}))\} \quad (1)$$

The outer summation in expression (1) comprises the hauls conducted with the specific T90 codend and the inner summation over length classes *l* in the data. Four different models were chosen as basic candidates to describe $r_{codend}(l, \boldsymbol{v_{codend}})$ for each codend and species individually: Logit, Probit, Gompertz and Richard. The first three models are fully described by the two selection parameters L50 (length of fish with 50% probability of being retained) and SR (difference in length between fish with respectively 75% and 25% probability of being retained) while the Richard model also requires one additional parameter (1/δ) that describes the asymmetry of the curve. The formulas for the four selection models, together with additional information, can be found in Lomeli (2019). Evaluating the ability of a model to describe the data sufficiently is based on calculating the corresponding *p*-value, which expresses the likelihood to obtain at least as big a discrepancy between the fitted model and the observed experimental data by coincidence. Therefore, for the fitted model to be a candidate to model the size selection data, this *p*-value should not be below 0.05 (Wileman et al, 1996). In case of a poor fit statistic (*p*-value < 0.05), the residuals were inspected to determine whether the poor result was due to structural problems when modeling the experimental data using the different selection curves or if it was due to overdispersion in the data (Wileman et al, 1996). Selection of the best model among the four considered in (1) is based on comparing the AIC values for the models. The selected model is the one with the lowest AIC value (Akaike, 1974).

Once the specific size selection model was identified for a particular species and T90 codend, bootstrapping was applied to estimate the confidence limits for the average size selection. We applied the software tool SELNET (Herrmann et al., 2012) for the size selection analysis and utilized the double bootstrap method implemented in this tool to obtain the confidence limits for the size selection curve and the corresponding parameters. This bootstrapping approach is identical to the one described in Millar (1993) and takes both within-haul and between-haul variation into consideration. The hauls for the codend with shortened lastridged were used to define a group of hauls. To account for between-haul variation, an outer bootstrap resample with replacement from the group of hauls was included in the procedure. Within each resampled haul, the data for each length class was bootstrapped in an inner bootstrap with replacement to account for within-haul variation. Each bootstrap resulted in a “pooled” set of data, which was then analyzed using the identified selection model. Thus, each bootstrap run resulted in an average selection curve. For each species analyzed, 1000 bootstrap repetitions were conducted to estimate the Efron percentile 95% confidence limits (Herrmann et al., 2012).

Modeling the size selection processes in the Sort-V grid and codend

Compared to for the codend with shortened lastridged (Fig. 16) is the size selection for the standard gear with the Sort-V grid combined with standard codend (Fig. 16) more complex as there are two selection processes: grid and codend. This is also reflected in experimental design with two covers to collected fish escaping through each of the selection processes involved. For this system Sistiaga et al. (2011) modelled the combined size selection by:

$$r_{combined}(l) = 1.0 - e_{Grid}(l) - e_{Codend}(l), \quad (2)$$

where $e_{Grid}(l)$, and $e_{Codend}(l)$ represent the escape probabilities through the grid, and codend, respectively.

In this study we applied the approach developed and described by Sistiaga et al. (2011) to model and estimate the combined size selection for the Sort-V grid and standard codend. Specifically, similar to other previous studies of sorting grids (Sistiaga et al., 2010; Larsen et al., 2016, 2018), Brinkhof et al. (2020) modelled the escape probability for the two grids based on a *CLogit* size selection model (Herrmann et al., 2013). In the *Clogit* model, the parameter *C* is assumed to be length independent and it quantifies the probability that a fish entering the grid zone contacts the grid with an orientation that provides it with a length-dependent probability of escaping through the grid (selectivity contact). For the fish that make selectivity contacts with the grid, the *CLogit* model assumes a traditional *Logit* size selection model defined by the parameters *L50* and *SR*. Thus, $e_{Grid}(l)$ was modeled by:

$$e_{Grid}(l, \boldsymbol{v_{Grid}}) = \frac{C_{Grid}}{1+\exp(\frac{\ln(9)}{SR_{Grid}} \times (l - L50_{Grid})}, \quad (3)$$

with the parameter vector $\boldsymbol{v_{Grid}} = (C_{Grid}, L50_{Grid}, SR_{Grid})$.

The codend was a traditional diamond mesh codend with a single mesh size attached to a sorting grid section, so $e_{Codend}(l)$ was modeled based on considering the same four models as for the codend with shortened lastridged:

$$e_{Codend}(l, \boldsymbol{v_{Grid}}, \boldsymbol{v_{codend}}) = \left(r_{Codend}(l, \boldsymbol{v_{codend}})\right) \times \left(1 - e_{Grid}(l, \boldsymbol{v_{Grid}})\right), \quad (4)$$

Where $r_{Codend}(l, \boldsymbol{v_{codend}})$ is given by Logit, Probit, Compertz or Richard model dependent on which model leads to lowest AIC-value for the model fit to the experimental data (expression (5)). The codend selection parameters then dependent on actual model is given by $\boldsymbol{v_{Codend}} =$

$(L50_{Codend}, SR_{Codend})$ **or** $(L50_{Codend}, SR_{Codend}, 1/\delta)$. For codend escape, equation (4) accounts for the condition that the fish has not previously escaped through the grid.

We used equations (2)–(4) to model the size selection in the combined size selection system comprising a Sort-V grid followed by the standard codend. Estimation was performed separately for each species. For the combined size selection L50 and SR was obtained based on a numerical method implemented in the analysis tool SELNET. This method is identical with the one applied by Sistiaga et al. (2010).

Catch data were collected using the three-compartment experimental design shown in Fig. 16, which included the codend (*C*), cover of the grid (*G*) to collect fish that escaped through the first grid, and the cover (*CC*) surrounding the codend to collect fish that escaped through the codend meshes. Thus, for each haul *j*, we had the number of individuals with length *l* collected in the codend (nC_{lj}), grid cover (nG_{lj}), and codend cover (nCC_{lj}). Thus, the species-specific size selection in the Sort-V grid combined with the standard codend and averaged over the *m* hauls conducted could be obtained by minimizing the following expression with respect to the parameters $\boldsymbol{v_{Grid}}$, and $\boldsymbol{v_{codend}}$ in the model comprising equations (2)–(4):

$$-\sum_{j=1}^{m}\sum_{l}\{nC_{lj} \times ln\big(r_{combined}(l, \boldsymbol{v_{Grid}}, \boldsymbol{v_{codend}})\big) + nG_{lj} \times ln\big(e_{Grid}(l, \boldsymbol{v_{Grid}})\big) + nCC_{lj} \times ln\big(e_{Codend}(l, \boldsymbol{v_{Grid}}, \boldsymbol{v_{codend}})\big)\}, \qquad (5)$$

Minimizing (5) with respect to its parameters is equal to maximizing the likelihood of the observed experimental data under the assumption that equations (2)–(5) describe the multi-nominal probabilities for observing a fish with length *l* in the codend or covers conditioned by the fish that entered the combined selection system comprising a Sort-V grid section and standaed codend.

The ability of the model (equation (2)–(4)) to describe the experimental data was like for the codend with shortened lastridged evaluated based on the *p*-value, model deviance versus degrees of freedom (DOF), and by inspecting how the model curves reflected the length-based trend in the data (Wileman et al., 1996). Like for the codend with shortened lastridged the data analysis was conducted using the software tool SELNET and uncertainties in estimated size selection obtained by using the double bootstrap method implemented in this tool.

Estimation of difference in size selectivity between selection systems

The difference in size selectivity $\Delta r(l)$ between the two selection systems Sort-V grid combined with standard codend (x) vs and codend with shortened lastridged (y) was estimated by:

$$\Delta r(l) = r_y(l) - r_x(l) \qquad (6)$$

The 95% confidence intervals for $\Delta r(l)$ were obtained based on the two bootstrap population results for $r_x(l)$ and $r_y(l)$, respectively. As they are obtained independently of each other, a new bootstrap population of results for $\Delta r(l)$ was created using (Larsen et al., 2018):

$$\Delta r(l)_i = r_y(l)_i - r_x(l)_i \;\; i \in [1 \ldots 1000] \qquad (7)$$

Finally, based on the bootstrap population, Efron 95% percentile confidence limits were obtained for $\Delta r(l)$ as described above.

Estimation of exploitation pattern and catch efficiency indicators

To evaluate how each of the three selection systems performed in the specific fishery, three exploitation pattern indicators *nP*–, *nP*+, and *dnRatio* were estimated separately for each species. *nP*− and *nP*+ quantify the retention efficiency for fish below and above the MRL (as percentages), respectively, whereas *dnRatio* represents the discard ratio in numbers and it denotes the percentage of undersized fish in the codend catch. These indicators can be used to summarize the catch patterns for specific gear in a specific fishery. The size selection properties provide information that is independent of the size structure of the population encountered by the gear during the fishing process, whereas these indicators depend directly on the size structure, thereby providing additional information to facilitate an evaluation of the catch performance of the selective system (Wienbeck et al., 2014). For the Sort-V grid combined with standard codend) and experimental setup (Fig. 16a), these indicators are given by:

$$\begin{aligned} nP- &= 100 \times \frac{\sum_j \sum_{l<MRL}(nC_{jl})}{\sum_j \sum_{l<MRL}(nC_{jl}+nG_{jl}+nCC_{jl})} \\ nP+ &= 100 \times \frac{\sum_j \sum_{l>MRL}(nC_{jl})}{\sum_j \sum_{l>MRL}(nC_{jl}+nG_{jl}+nCC_{jl})}, \qquad (8) \\ dnRatio &= 100 \times \frac{\sum_j \sum_{l<MRL}(nC_{jl})}{\sum_j \sum_{l}(nC_{jl})} \end{aligned}$$

where the sum of j is over the hauls and l is over the length classes. Ideally, for a target species, *nP−* and *dnRatio* should be low (close to zero), whereas *nP+* should be high (close to 100%), i.e., retain all individuals over the MRL that enter the codend.

For the shortened lastridge codend and experimental design (Fig 16) the estimation of the indicators simplifies to:

$$\begin{aligned} nP- &= 100 \times \frac{\sum_j \sum_{l<MRL}(nC_{jl})}{\sum_j \sum_{l<MRL}(nC_{jl}+nCC_{jl})} \\ nP+ &= 100 \times \frac{\sum_j \sum_{l>MRL}(nC_{jl})}{\sum_j \sum_{l>MRL}(nC_{jl}+nCC_{jl})} \qquad (9) \\ dnRatio &= 100 \times \frac{\sum_j \sum_{l<MRL}(nC_{jl})}{\sum_j \sum_{l}(nC_{jl})} \end{aligned}$$

The double bootstrap method described in the previous section was used to estimate the Efron 95% percentile CIs for the indicator values. The CIs considered the effects of variations in both the between-haul selection and the population entering the gear, in addition to the uncertainty in individual hauls because the number of fish caught in each haul is finite.

4.1.4. Results

In total 20 hauls were conducted during the cruise alternating between the configuration with the Sort-V grid and regular codend and the configuration with the shortened lastridge codend (Table 7). 11 815 cod and 4 894 haddock were caught, and length measured (Table 7).

Table 7. Overview over the hauls conducted depth at towing start, towing time, and number of fish caught in each compartment.

				No. Cod			No. Haddock		
Haul No.	**Trawl configuration**	**Depth (m)**	**Towing time (hh:mm)**	**nG**	**nC**	**nCC**	**nG**	**nC**	**nCC**
1	Short lastridge codend	292	00:31	-	284	32	-	104	148
2	Sort-V & regular codend	292	00:45	101	583	1	145	50	1
3	Sort-V & regular codend	290	00:50	46	1352	3	109	82	2
4	Short lastridge codend	291	00:37	-	254	21	-	69	74
5	Short lastridge codend	292	00:43	-	521	9	-	38	7
6	Sort-V & regular codend	291	00:47	99	1751	9	247	116	5
7	Sort-V & regular codend	298	00:44	71	431	4	298	66	23
8	Short lastridge codend	225	00:45	-	293	17	-	83	88
9	Short lastridge codend	293	00:39	-	482	6	-	80	93
10	Sort-V & regular codend	293	00:47	64	648	1	129	33	3
11	Sort-V & regular codend	305	00:32	67	457	3	141	52	3
12	Short lastridge codend	304	01:01	-	42	1	-	109	20
13	Short lastridge codend	299	01:21	-	278	20	-	150	179
14	Sort-V & regular codend	292	00:47	52	574	2	179	56	6
15	Sort-V & regular codend	296	00:36	56	355	1	188	63	10
16	Short lastridge codend	300	01:13	-	561	13	-	212	183
17	Short lastridge codend	298	01:00	-	1189	16	-	161	187
18	Sort-V & regular codend	293	00:57	39	337	3	312	68	4
19	Sort-V & regular codend	294	00:38	16	167	3	230	69	2
20	Short lastridge codend	297	00:42	-	466	14	-	112	105

The models used to describe the escape and retention of haddock and cod for the different configurations reflected the main trends in the experimental data well, i.e. *p-value* > 0.5 (Fig. 17-21, Table 8). For one case the *p*-value was below 0.05, however inspecting the residuals demonstrated that the poor fit statistics were caused by over-dispersion (Table 8).

Sort-V grid & regular codend

The size selectivity curves for both cod and haddock caught with the configuration with the Sort-V grid and the regular codend demonstrated that by far most of the fish escape trough the grid, and that few fish escape through the codend meshes (Fig. 17). The retention probability curves show that few fish below MRL are caught with this configuration. However, the curves also show that a large proportion of fish above the MRL escape, especially for haddock (Fig. 17). This is corroborated by the catch pattern indicators, which estimate that with this configuration the catches contained 14.2 % (CI: 7.4-23.0) cod, and 2.3 % (CI: 1.1-3.8) haddock below MRL (Table 8). The retention of cod above the MRL was 93.1 % (CI: 89.8-95.2), and only 32.8 % (CI: 28.6-37.9) for haddock (Table 8). The discard ratio of 0.4 % and 2.6 % for cod and haddock respectively is far below the legislated limit of 15 %. The L50-values was fairly similar for both species, i. e. ~51 cm.

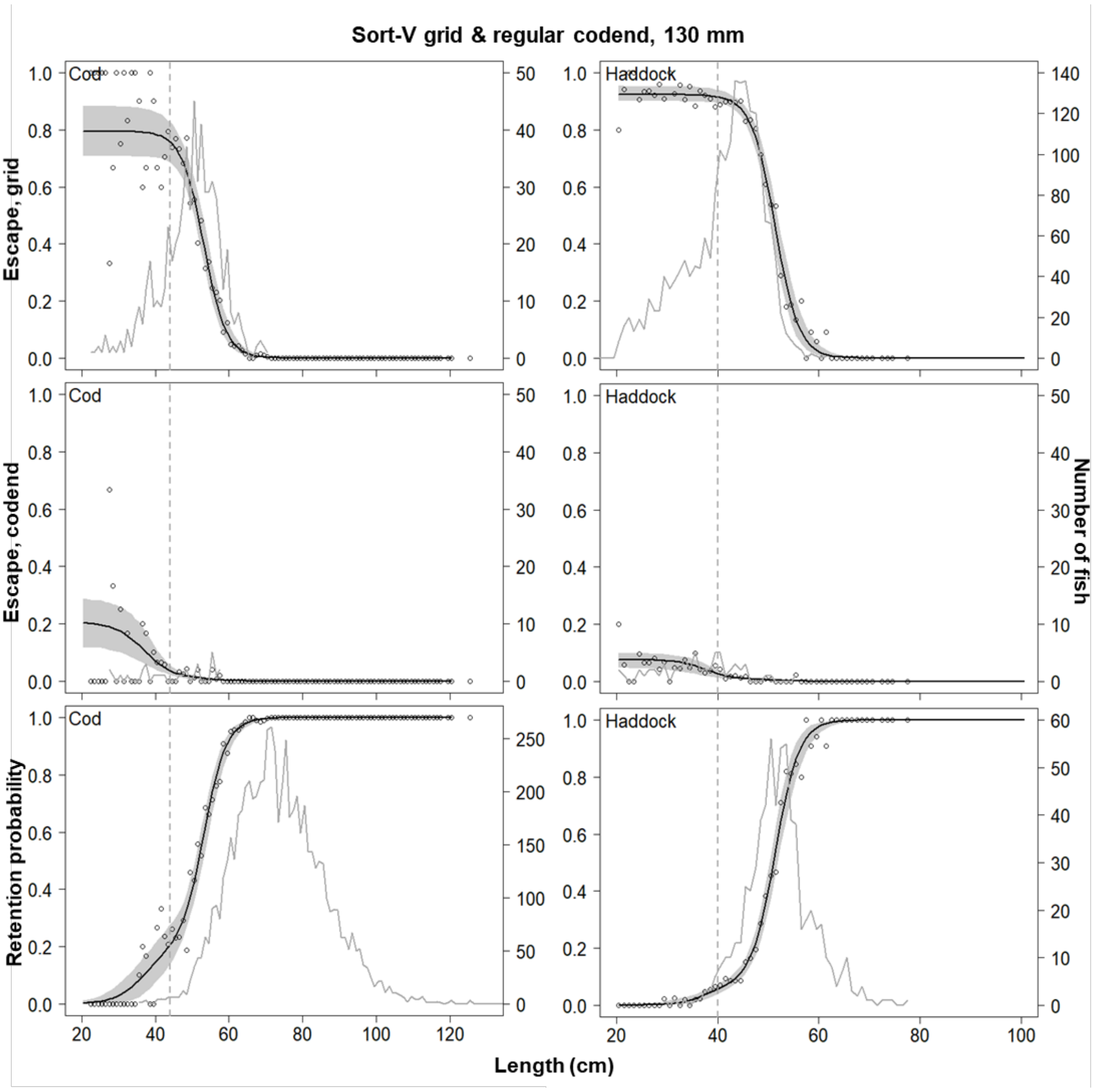


Figure 17. Length-dependent probabilities of escape in the conventional gear configuration, i.e. Sort-V with regular 130 mm codend, as well as the combined retention for both cod (left column) and haddock (right column).

The solid curves represent the models fitted to the data (circles) with the 95% CI's (grey area). The frequency curves in grey represent the number of fish caught in each length class in each compartment. The stippled vertical grey lines denote the MRL for cod (44 cm) and haddock (40 cm).

For the configuration with the codend with shortened lastridges the L50-values were also similar for both species (~41 cm), and thus closer to the MRL. This results in that this configuration catches more fish both above and below the MRL, as demonstrated by the size selectivity curves for both cod and haddock (Fig. 18). This is also corroborated by the catch pattern indicators, which catches in the codend with the short lastridges contained 24.6 % (CI: 17.5-33.6) cod below the MRL, and 8.4 % (CI: 5.6-12.9) haddock below the MRL (Table 8). On the other hand, the catches above MRL increased to 99.0 % (CI: 98.4-99.4) for cod and 77.8 (CI: 72.5-83.4) for haddock. The discard ratio for cod was 0.8 % and for haddock 6.4 %, and thus still far below the legislated limit of 15 % (Table 8).

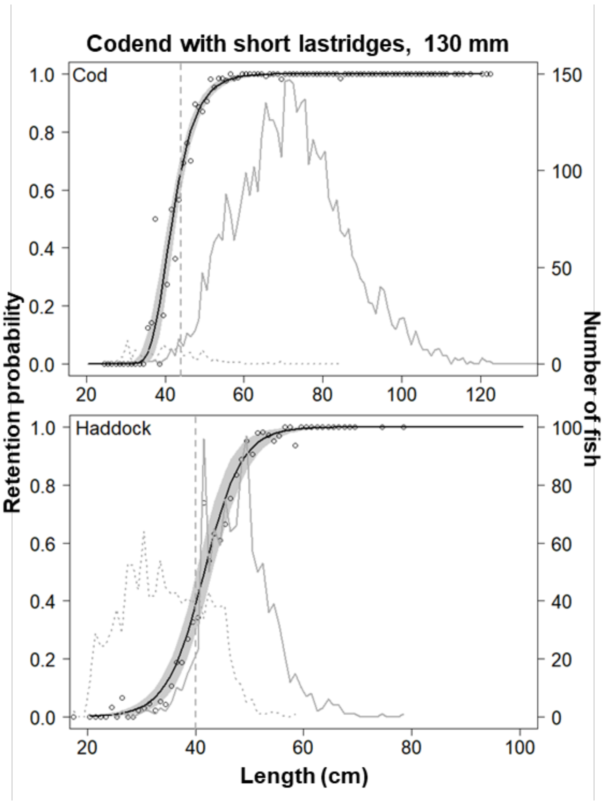


Figure 18. Length-dependent probabilities of retention in the gear configuration with the codend with shortened lastridges for cod (upper), and haddock (lower). The solid curves represent the models fitted to the data (circles)

with the 95% CI's (grey area). The frequency curves in grey represent the number of fish caught in each length class in the cover (dotted line), and codend (solid line). The stippled vertical grey lines denote the MRL for cod (44 cm) and haddock (40 cm).

Removing the effect of the Sort-V grid provided the results for the size selectivity that solely found place in the regular codend (Fig. 19). Especially for cod, fishing with a regular codend with a mesh size of 130 mm without a sorting grid would retain large proportion of fish below the MRL while releasing few fish above MRL (Fig. 19). The L50-value of 35.9 cm for cod and 38.2 cm for haddock are well below the MRL (Table 8). The catch indicators estimated nearly full retention of fish above the MRL (Table 8). However, the retention below the MRL was estimated to be 64.1% for cod and 29.8% for haddock (Table 8). The discard ratio was still below the limit of 15 %, i.e. 0.4% and 1.6% for cod and haddock, respectively (Table 8).

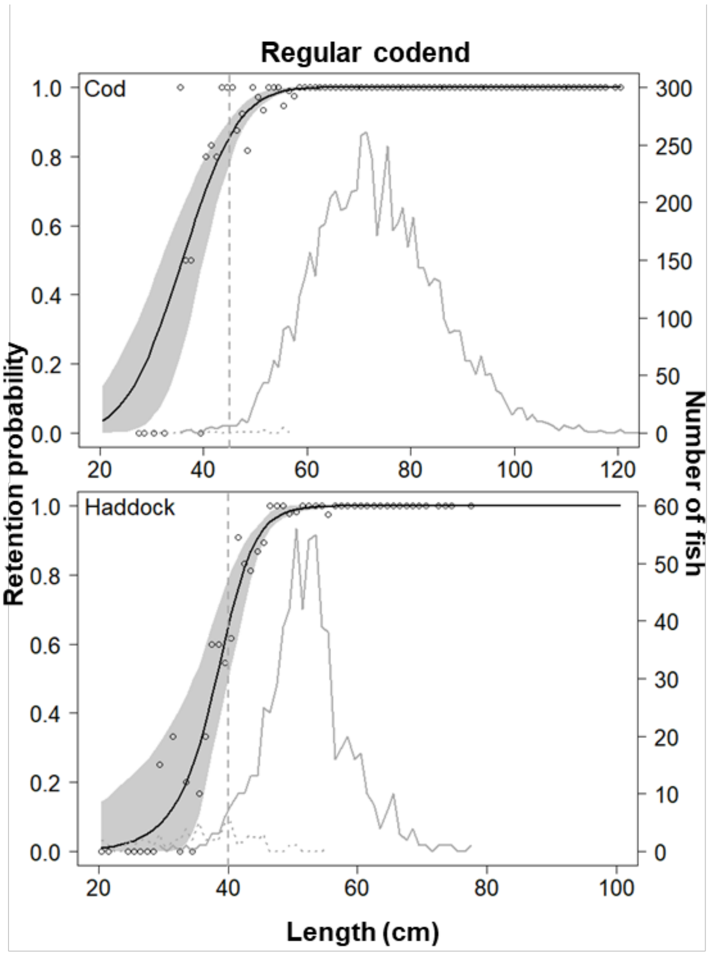


Figure 19. Length-dependent probabilities of retention in the gear configuration with the regular codend without the effect of the Sort-V grid for cod (upper), and haddock (lower). The solid curves represent the models fitted to

the data (circles) with the 95% CI's (grey area). The frequency curves in grey represent the number of fish caught in each length class in the cover (dotted line), and codend (solid line). The stippled vertical grey lines denote the MRL for cod (44 cm) and haddock (40 cm).

Table 8. The estimated size selectivity parameters, L50 and SR (Selection Range), catch pattern indicators for the catch below MRL (nP-), catch above MRL (nP+), and discard ration (nDRatio) in percentage, and the fit statistics.

	Sort-V & codend		**Short lastridge codend**		**Regular codend**	
	Cod	**Haddock**	**Cod**	**Haddock**	**Cod**	**Haddock**
L50 (cm)	51.74	51.02	41.83	41.76	35.91	38.17
SR (cm)	9.58	5.68	6.37	7.41	11.5	6.82
nP- (%)	14.2 (7.39-23.02)	2.28 (1.06-3.78)	24.64 (17.53-33.63)	8.39 (5.58-12.90)	64.10 (41.86-81.58)	29.82 (15.52-58.06)
nP+ (%)	93.12 (89.8-95.16)	32.80 (28.55-37.89)	98.97 (98.38-99.35)	77.83 (72.45-83.44)	99.76 (99.62-99.92)	97.11 (95.50-98.55)
nDRatio (%)	0.38 (0.20-0.68)	2.60 (1.06-4.52)	0.78 (0.39-1.40)	6.44 (4.70-8.36)	0.38 (0.19-0.60)	2.60 (1-124.32)
Model	Triple Logit	Triple Logit	Gompertz	Logit	Probit	Richard
p-value	1.000	0.999	0.999	0.028	1.000	0.999
DOF	195	107	94	51	88	49
Deviance	103.6	59.8	50.2	72	39.6	20.9

Comparison of size selectivity and catch efficiency between the configurations

Comparing the size selectivity curves for the Sort-V and the regular codend with the result from the codend with short lastridges demonstrated a significant difference for nearly all length groups for both cod and haddock (Fig. 20). The delta plots corroborate this founding and demonstrates that the significant difference is largest for cod and haddock above the MRL (Fig. 20). The catch pattern indicators demonstrated that the difference in catch efficiency between the codend with short lastridges and the Sort-V with regular codend did not significantly affect the retention of cod below MRL, however the retention above MRL was increased by 5.9% (CI: 3.8-9.1) with the shortened lastridge codend (Table 9). For haddock, the codend with short lastridges retained 6.1% (CI: 3.1-11.0) more fish below MRL, and 45% (CI: 37.0-52.2) more fish above the MRL compared to the configuration with the Sort-V with regular codend (Table 9). Also, the discard ratio increased significantly with 3.8% (CI: 1.2-6-6.4) from 2.6% to 6.4% (Table 8 and 9).

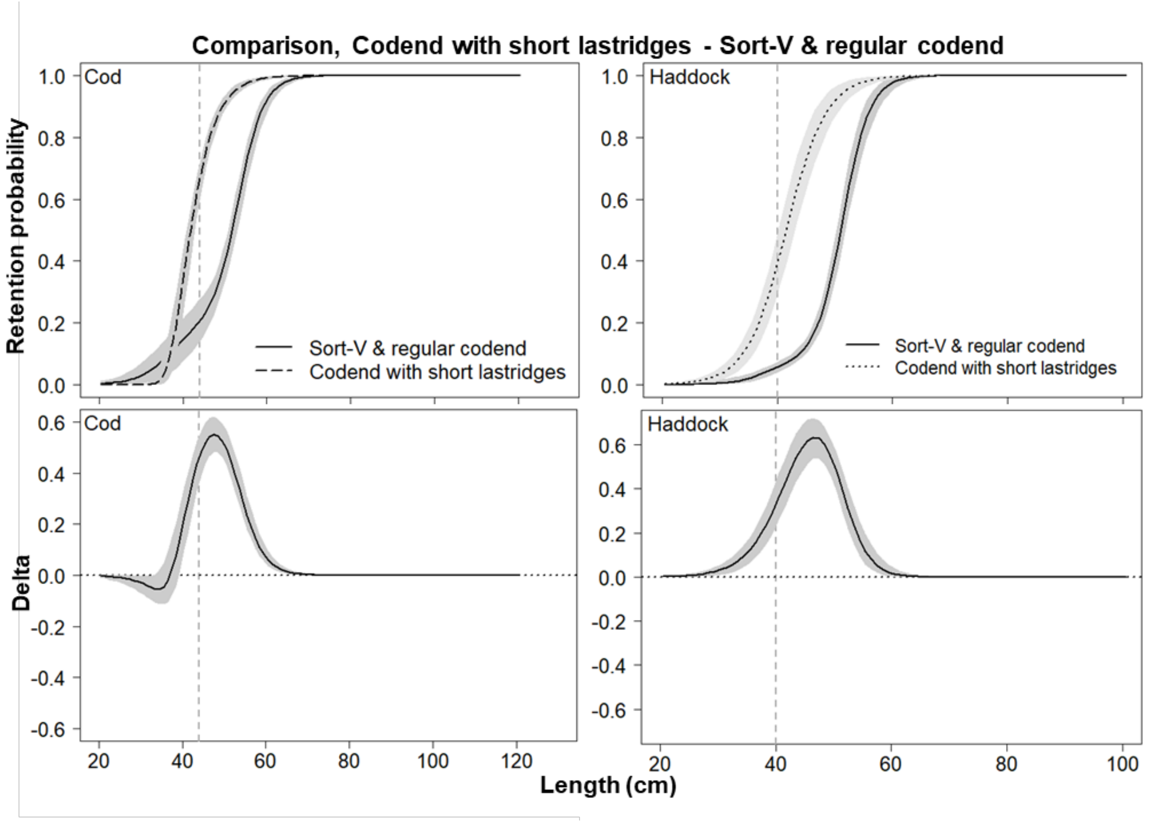


Figure 20. Comparison of the estimated length-dependent probabilities of retention of the two gear configurations tested (upper row), and differences in the selection properties between the gears expressed as delta retention probability (lower row) for cod (left column) and haddock (right column). Grey areas represent the 95% CI's. The stippled vertical grey lines denote the MRL for cod (44 cm) and haddock (40 cm).

Comparing the results between the configuration between the Sort-V including codend and the regular codend demonstrated that the latter retains significantly more cod and haddock both above and below the MRL (Fig. 21, Table 9). The same results where obtained when comparing the codend with short lastridges with the regular codend, however, this significance was for fewer length groups (Fig. 21, Table 9).

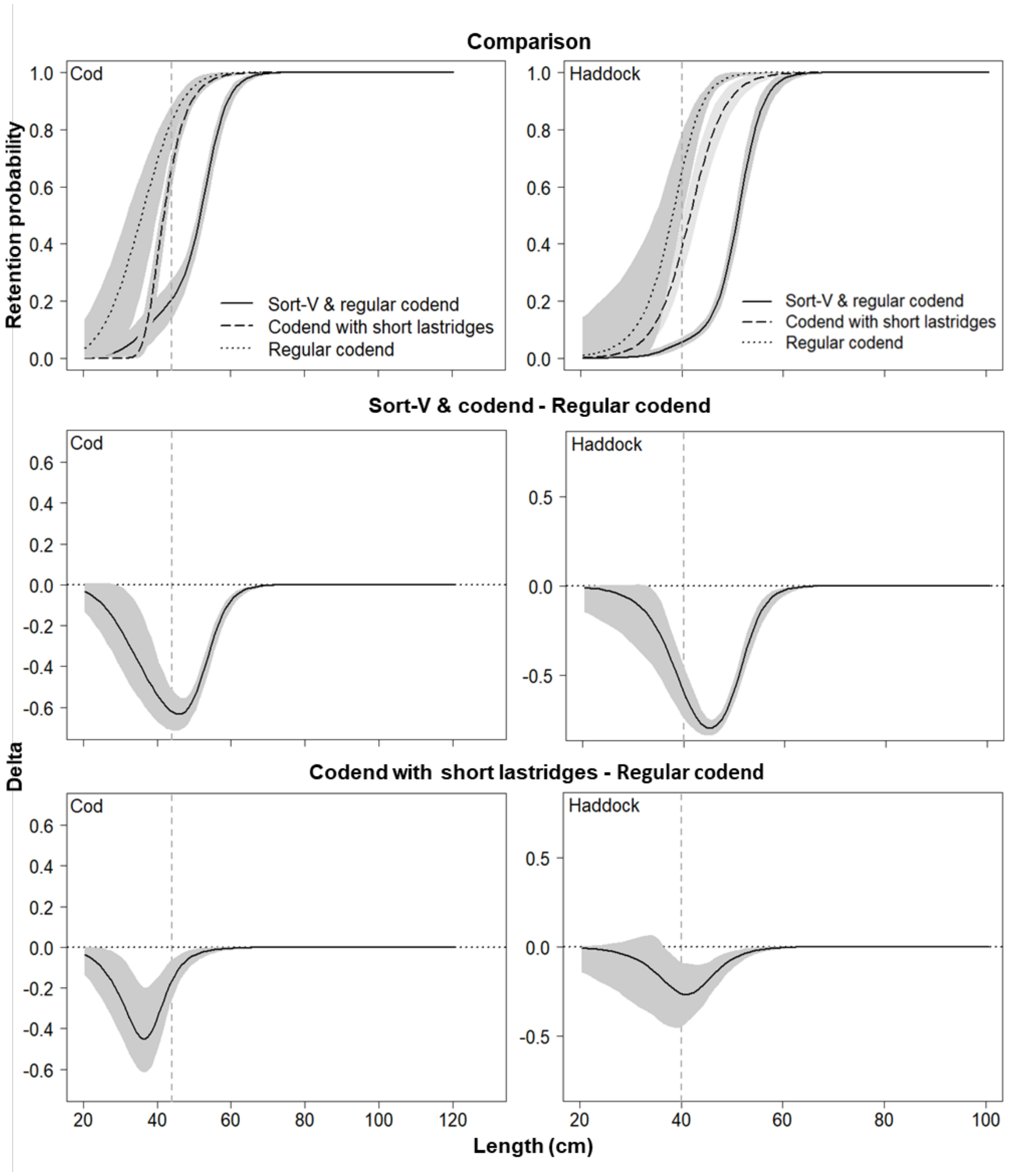


Figure 21. Comparison of the estimated length-dependent probabilities of retention of Sort-V and codend configuration, the codend with shortened lastridge ropes confirugration and the regular codend without the effect from the Sort-V grid (upper row) for cod (left column) and haddock (right column). The differences in the selection properties between the Sort-V and codend configuration compared to the effect from the codend solely (middle row), and the codend with short lastridges compared to the regular codend without Sort-V is expressed as delta retention probability. Grey areas represent the 95% CI's. The stippled vertical grey lines denote the MRL for cod (44 cm) and haddock (40 cm).

Table 9. Percentage difference in the catch pattern indicators between the three configurations for both cod and haddock.

Species	**Gear type**	**Δ nP- (%)**	**Δ nP+ (%)**	**Δ nDRatio**
Cod	Short lastridge codend - SortV & codend	10.44 (-0.23-21.95)	**5.85 (3.81-9.09)**	0.4 (-0.08-1.04)
	SortV & codend - Regular codend	**-49.90 (-69.08--23.53)**	**-6.64 (-9.89--4.64)**	0.00 (-0.34-0.36)
	Short lastridge codend - Regular codend	**-39.46 (-59.55--15.44)**	**-0.79 (-1.40--0.37)**	0.40 (-0.08-0.97)
Haddock	Short lastridge codend - SortV & codend	**6.11 (3.06-10.96)**	**45.03 (36.95-52.21)**	**3.84 (1.20-6.36)**
	SortV & codend - Regular codend	**-27.54 (-56.58--13.37)**	**-64.31 (-68.91--59.15)**	0.00 (-2.39-2.36)
	Short lastridge codend - Regular codend	**-21.43 (-49.60--5.80)**	**-19.28 (-25.16--13.23)**	**3.84 (1.39-6.37)**

4.1.5. Discussion

Selectivity in trawls as a measure to reduce unwanted by-catch, either size or species, has gained much attention over the last decades worldwide (Walsh et al., 2002; Graham 2010). Also in the Northeast Atlantic demersal trawl fishery for gadoids by far most of the scientific studies have been devoted to selectivity (Kennelly and Broadhurst, 2021). After the decline and re-building of the NEA-cod stock in the late 80'ties and early 90'ties the importance of strict by-catch regulations became evident and were gradually implemented in the fishery (Hammer and Hoel, 2012; Gullestad et al., 2015). The invention, development and implementation of the rigid sorting grid called "Nordmøregrid" in the early 90'ties in the shrimp trawl fishery nearly mitigated the by-catch of fish, releasing all the fish that do not fit between the 19 mm bar spacings (Isaksen et al., 1992; Larsen et al., 2018). Due to its success the same but opposite principle of the rigid sorting grid was then further developed by the same scientists so that it could be applied in demersal fish trawls releasing most of the fish below the MRL (Larsen and Isaksen, 1993). The size selective sorting grid in demersal trawls with 55 mm bar spacing has been used since 1993 and became mandatory in 1997 and gave the fishers access to areas that otherwise would be closed for fishing due to too catches of juvenile fish.

Compared to the poor size selectivity in diamond meshed codends, that multiple studies have reported (Robertson and Stewart, 1988; Herrmann, 2005a,b; Sala et al., 2008; Wienbeck, 2011), the development of the sorting grid to a large degree mitigated the problem of by-catch of juvenile fish. The increased demands on fisheries with regards to environmental impact, sustainability, catch quality and fish welfare has shifted the focus to not only include selectivity and by-catch mitigation but also seabed impact, greenhouse gas emissions, catch quality and fish welfare and catch efficiency. This means that on the one hand its important to mitigate catches of unwanted species and fish below the MRL, while on the other hand its important to maximize catch efficiency for fish above the MRL. Reduced catch efficiency of fish above the MRL because of size selectivity requires increased fishing effort in order for the vessels to catch their quota, and consequently lead to increased seabed impact, fuel consumption and greenhouse gas emission as well as reduced profitability for the fishers. Several recent studies have demonstrated some drawbacks with the sorting grid. Under high entry rates fishers experience clogging of the grid section causing reduced catch control, and in worst case breakage of the gear. (Grimaldo et al., 2014; Sistiaga et al., 2016). Several studies have also reported varying size selective properties (Sistiaga et al., 2016; Brinkhof et al., 2020). A recent study reported that up to 77.4% of haddock and 16% of the cod above the MRL are released through the grid (Brinkhof et al., 2020).

One possible solution to the issues with the sorting grid is to omit the grid and solve the original problem, i.e. the closing of the meshes in the diamond mesh codend when the catch accumulates in the aft.

4.2. 4-panel Sort-V sorting grid design

4.2.1. Summary

In many trawl fisheries around the world codend size selectivity is supplemented by additional sorting devices. In the Barents Sea, sorting grids are compulsory and fishermen are allowed to used different grids and different configurations within the same type of grid that in principle have the same size sorting properties i.e. grid sections constructed in 2- and 4-panels. The present study compared the size selective properties of a Sort-V steel grid mounted in three different netting section configurations: 2-panel section, 4-panel section and 4-panel section with a modified lifting panel. The results showed that the 4-panel grid configurations tested retained more cod and haddock, both above and below the minimum legal size. Further, the standard 4-panel configuration showed significantly lower contact values than the 2-panel configuration, which were to a large extent solved by modifying the lifting panel. Overall, the results of the study demonstrate despite having been labeled as stable sorting devices, grids are sensitive to the section netting configuration they are installed in and that certain elements in the construction can have major consequences for their performance.

4.2.2. Introduction

Trawls are very diverse and represent one of the most important fishing gears worldwide. Some of the main reasons for the popularity of trawls is that they are very adaptable, robust and efficient, however, the application of this gear is not exempt of challenges and controversy. In addition to issues related to energy consumption and seabed disturbance, trawls have often been criticized for their poor and unstable selective properties.

Selectivity in trawls has been much studied in the last four decades and most of the research carried out has focused in the codend, which in the majority of fisheries and trawl configurations is the most selective part of the gear. The selectivity properties of a codend have been demonstrated to vary depending on multiple parameters like mesh size, orientation of the meshes (e.g. T0 or T90), twine thickness or codend diameter. Further, as the catch builds up, the increasing longitudinal forces in the meshes in the codend change their shape and consequently their selective properties as well.

In the pursuit of more stable selectivity results, the authorities of different countries have considered, and in some cases implemented, additional devices like square mesh panels or sorting grids to supplement codend size selectivity (Herrmann et al., 2015; Cuende et al., 2020; Sistiaga et al., 2008; Brinkhof et al., 2020). This is the case for Norway and Russia, who implemented the compulsory use of sorting grids in the Barents Sea gadoid fishery in 1997

(Larsen and Isaksen, 1993). Today, fishermen participating in this fishery can use three different types of grids, the Sort-x, Sort-V and Flexigrid (Herrmann et al., 2013), all installed in the extension piece in front of the codend and all with a minimum bar spacing of 55 mm. In addition to the grid, fishermen are obliged to use a diamond mesh codend with a minimum mesh size of 130 mm. In this configuration, grids have been reported to be the major contributor to fish size selectivity and are supposed to supplement codend size selectivity because they are installed prior to the codend, meaning that only the fish that do not escape through the grid will reach the codend (Brinkhof et al., 2020). In addition, grids are rigid or semirigid constructions with the same bar spacing that are expected to perform steadily independent on catch size. However, the grids used in the Barents Sea have been also reported to perform differently between cruises (Brinkhof et al., 2020), have shown to be susceptible to changes in the netting section where they are installed (Sistiaga et al., 2016) and be dependent on elements like the lifting panel to perform efficiently (Grimaldo et al., 2015).

In 2016, the Norwegian regulations introduced the use of a 4-panel Sort-V section as a legal alternative to the original 2-panel Sort-V version for the Barents Sea gadoid fishery. Despite having tested the 4-panel version in a flume tank, this construction was never tested at sea nor directly compared to the original 2-panel version. The 4-panel construction was simply assumed to have size selective properties comparable to those of the original 2-panle grid. However, considering that earlier studies have reported differences between similar grid constructions built of 2- and 4-panels (Sistiaga et al., 2016), and that the lifting panel is different in the 2- and 4-panels sections, this comparison should have been carried out. The presence/absence of the lifting panel has earlier been demonstrated to be of major importance for the performance of the Sort-V grid as it can influence the contact probability of fish with the grid (Grimaldo et al., 2015). The contact probability defines the fraction of fish that is subjected to a length-dependent size selectivity process in the grid (Sistiaga et al., 2010).

Cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) are the mail species targeted in this fishery. In addition, redfish (*Sebastes* spp.) is one of the main bycatch species, which can be caught at substantial numbers at times. Different fish species can act differently when they are surrounded by the trawl netting, and these three species have been earlier been reported to have enter the trawl at different positions in the gear and behave differently in the aft of the trawl. Therefore, it is possible that the changes in the construction of the grid section could influence the selectivity of different species in a different manner.

The aim of the present study was to compare 2- ad 4-panel Sort-V grid sections and to evaluate the importance of the lifting design for the performance of this sorting grid. Specifically, the study aimed at answering the following research questions:

- Does the 4-panel design of the Sort-V grid result on similar selectivity properties for cod, haddock and redfish?
- Does the different design of the lifting panel in the 2- and 4-panel Sort-V sections result on different contact probability with the grid for cod, haddock and redfish?
- Is it possible to improve the selectivity performance of the 4-panel Sort-V grid section by modifying the lifting panel?

4.2.3. Materials and methods

Experimental design and data collection

Experimental fishing was conducted onboard R/V “Helmer Hanssen”. We used an Alfredo 3 trawl built of two panels with 420 meshes in circumference. The netting used was made of 4 mm polyethylene (PE) twine and the nominal size of the meshes in the trawl was 155 mm. In addition to the trawl we employed a set of Injector Scorpion otter boards (weighing 3100 kg, with an area of 8 m^2 each) connected by 60 m long sweeps with 3 m long backstraps followed by 7 m long connector wire. To protect the sweeps from excessive abrasion a Ø53 cm steel bobbin was inserted in the middle of the sweeps. The ground gear used was 46 m long and comprised of 18.9 m long rock-hopper gear (Ø53 cm) in the middle and a 14 m long (Ø 19 mm) chain with three equally spaced steel bobbins (Ø53 cm) in each of the sides. The rock-hopper gear was attached to the 19.2m long fishing line in the trawl. The headline of the trawls was 36.5 m long.

During the trials we tested three different Sort-V sorting grid configurations: a standard 2-panel section, which is the configuration mostly used by the fleet and was identical to the one described in the legislation (Fig. 22); a 4-panel section identical to the one described in the legislation (Fig. 23); and a 4-panel section with a modified lifting panel (Fig. 24). The reason for testing this third configuration was that the lifting panel has substantial differences between the 2- and 4-panel configurations and it was speculated in advance that this could be a potential source for differences between the 2- and 4-panel configurations. The section and grid used for the last two configurations was the same i.e. only the lifting panel was modified in the section. The grids in the two sections tested were identical in size (1650 x 1234 mm) and the bar spacings in them were measured to be 54.8 ± 1.1 mm (mean ± SD) and 55.4 ± 1.2 mm and 55.4 ± 1.2 mm for the 2-panel section and 4-panel section (with and without the modified lifting panel), respectively. Due to that the trawl and codend we used were identical through the trials and constructed in 2-panels, a 2-to 4-panel transition section and a 4- to 2-panel transition section were applied in front and behind the grid section when the 4-panel grid section was employed (Fig. 23 and Fig. 24). When the 2-panel was section was applied, extension pieces were used both in front and behind the grid section (Fig. 22) so that the length of the gear was as similar as possible in both cases.

Subsequent to the grid section and the extension piece we attached a codend, which was 12 m long and had 60 meshes in circumference. The codend was built of single braided Ø8 mm hotmelt PE twine, with a mesh size of 133.8 ± 2.2 mm. The minimum mesh size in the codend in this area is 130 mm and this type of codend is very widespread among the fleet.

The experimental design followed the covered-codend method (Wileman, 1996). Thus, in all three configurations tested a cover was mounted over the grid to catch the escapees. The cover had an inner mesh size of 45.8 ± 1.5 mm and was reinforced with a large mesh netting to lower the risk for breakage. To keep the cover clear from the grid and avoid blockage seven floats were installed along the cover.

It was of interest to study the contribution of the codend to the overall selectivity in the system. Therefore, when the 2-panel grid configuration was used a cover over the entire codend was installed to catch the escapees. To ensure that the cover stayed clear from the codend the front part of the cover was equipped with six floats, three kites, and a 12 kg piece of chain on the top, side and bottom part of the codend, respectively. Also, twelve kites were attached to the cover around the bulk of the catch in the codend (see Brinkhof et al. (2020) for further details on the cover. The cover had a mesh size of 51 ± 1.3 mm (mean ± SD) and was strengthened with an outer layer of large meshed netting in the aft. When the 4-panel configurations were used, an inner-net with a nominal mesh size of 40 mm and low hanging ratio that did not allow escapees was employed.

The trawl was monitored by acoustic sensors measuring door spread, trawl height, and catch volume. The latter was installed so that it would warn when the catch exceeded approximately 1.5 tons. The total length of all cod and haddock above 20 cm retained in either the codend or any of the covers was measured to the nearest centimeter below.

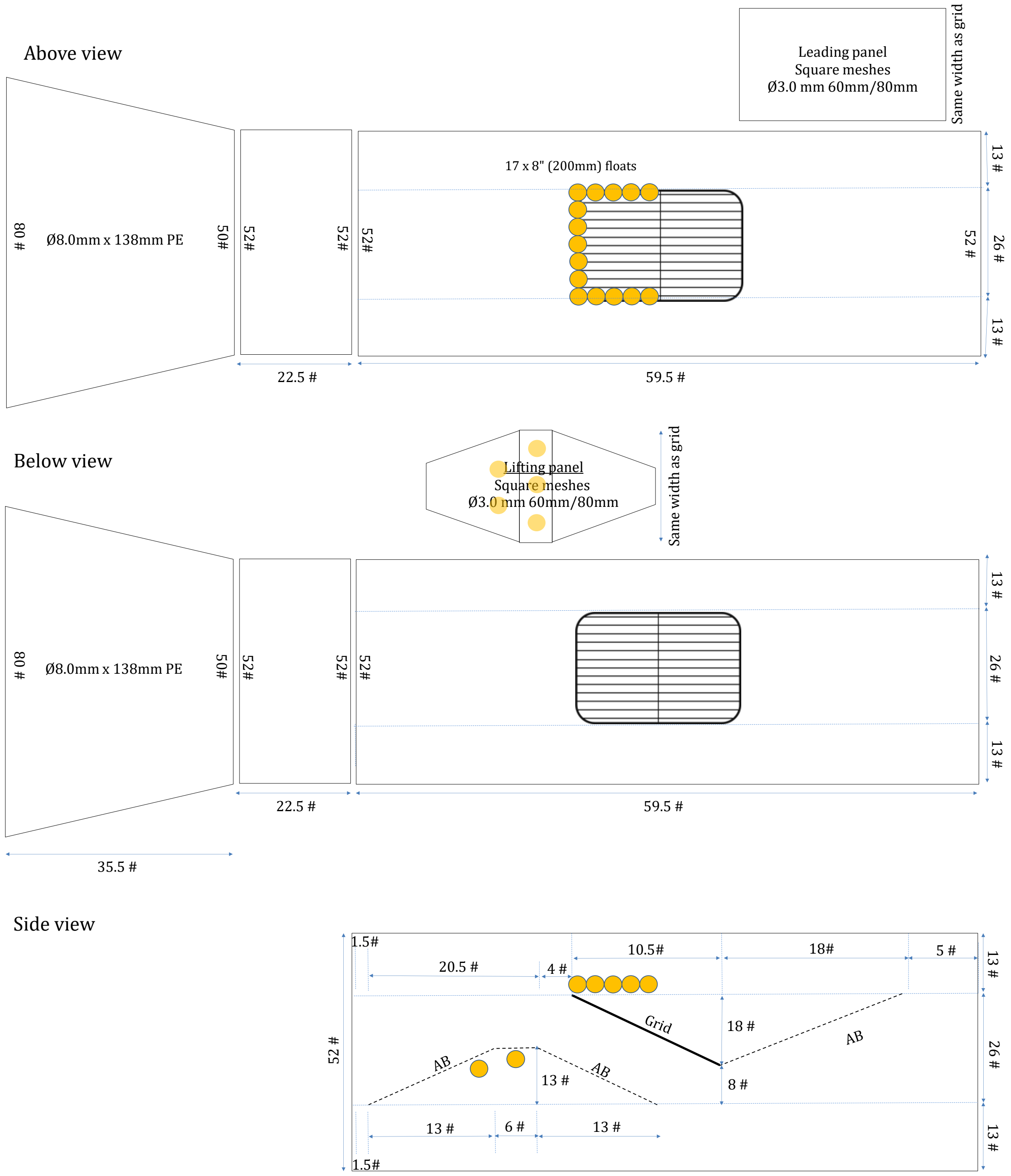


Fig. 22: Construction details of the 2-panel grid section.

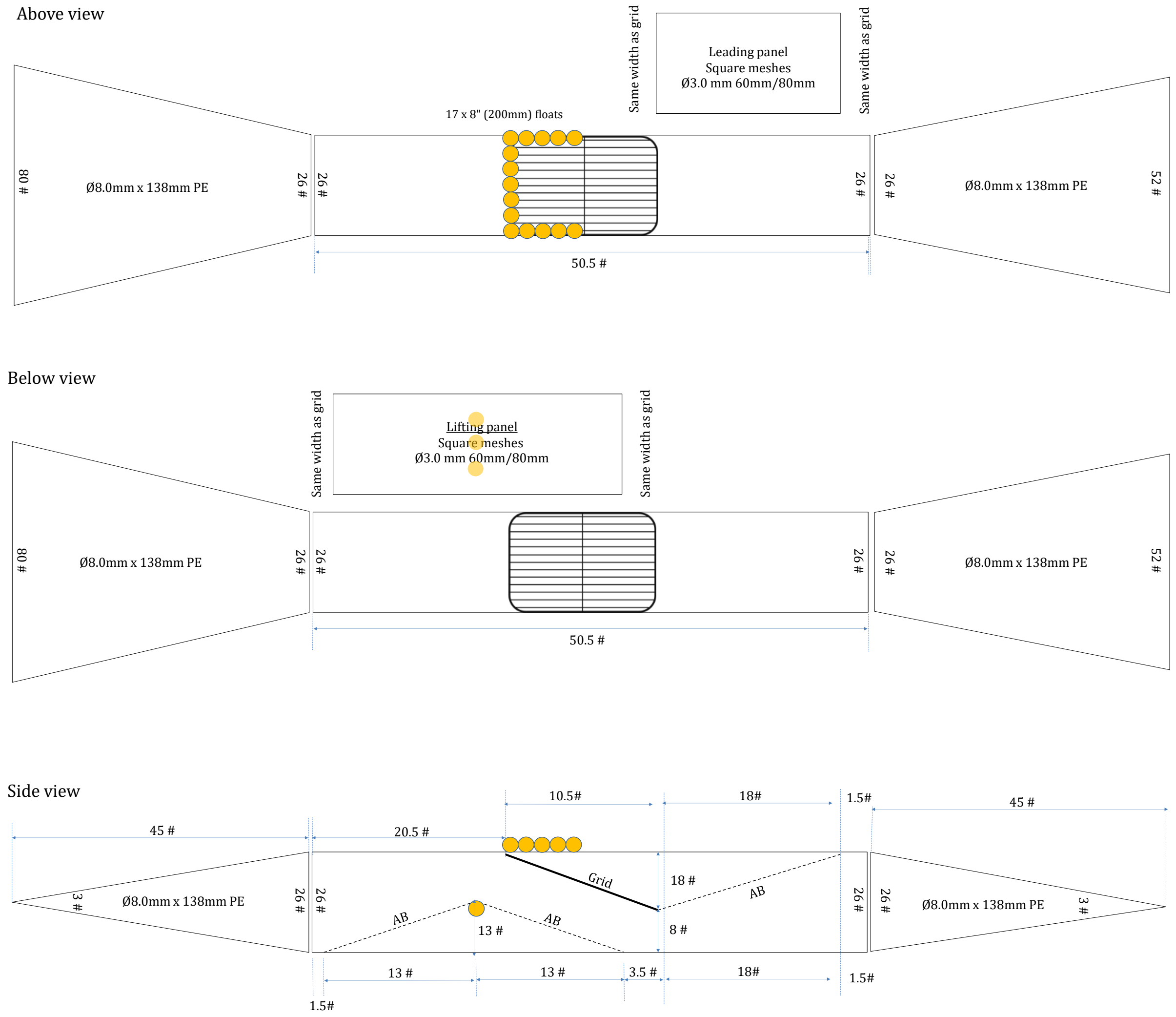
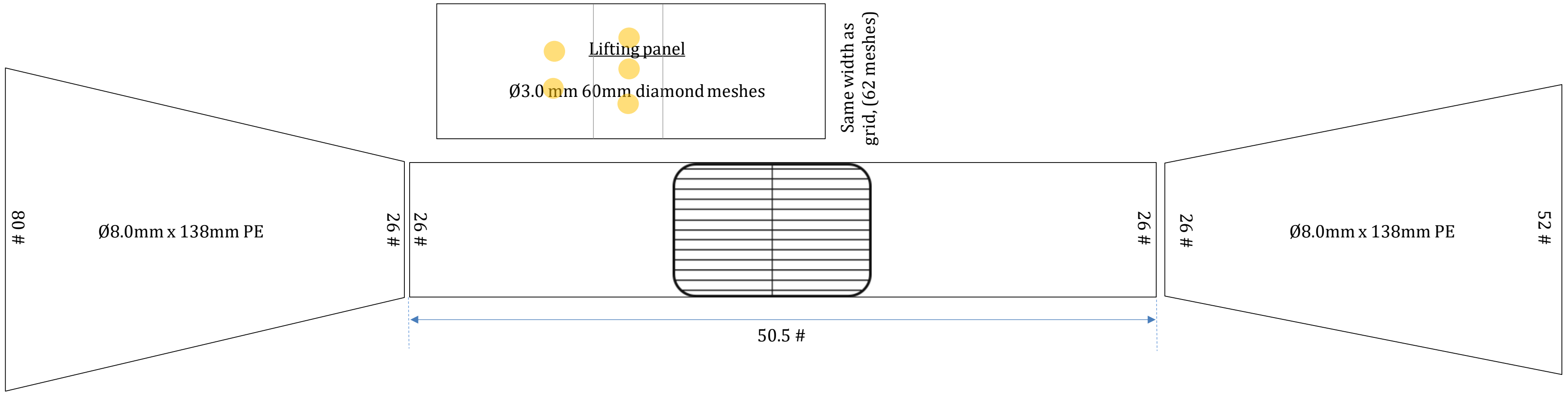


Fig. 23: Construction details of the 4-panel grid section.

Below View



Side View

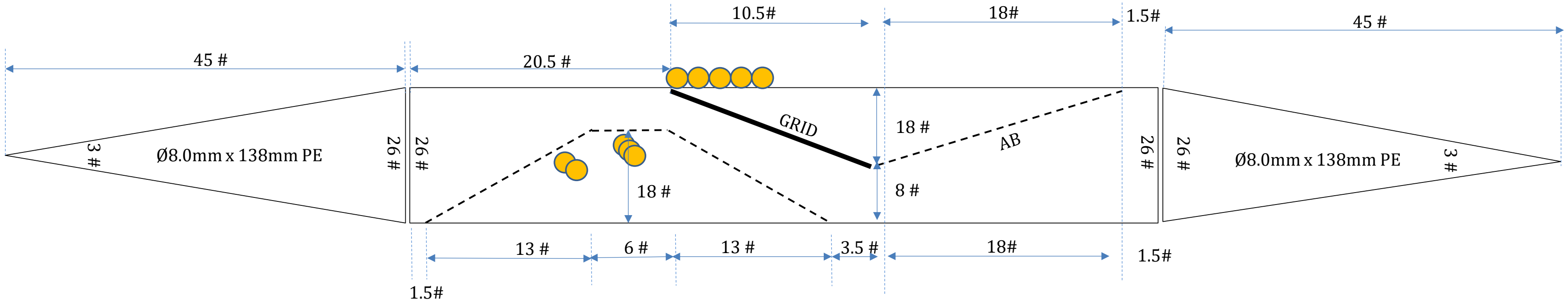


Fig. 24: Construction details of the modified 4-panel grid section.

Data analysis

The size selection in the grid sections was modelled based on the *CLogit* model (Herrmann et al., 2013b), which accounted for that not necessary all fish entering the grid section contacted the grid:

$$CLogit(l, C, L50, SR) = 1.0 - \frac{C}{1.0 + exp\left(\frac{ln(2.0)}{SR} \times (l - L50)\right)} \qquad (1)$$

Only the fish contacting the grid obtain a size dependent probability for escaping through it. In the *CLogit* model, *l* denotes fish length and parameter *C* quantifies the assumed fish length independent probability for a fish entering the grid zone to also contact it in a way that provides it a length dependent probability for escaping through the grid. Thus, *C* undertakes a value between 0.0 and 1.0, where a value at 1.0 would mean that every fish entering the grid zone would contact the grid. A value at 0.4 on the other hand would mean that only 40% of the fish entering the grid zone would contact it. For the fish contacting the grid the *CLogit* model assumes a traditional *Logit* size selection model (Wileman et al., 1996) defined by the parameters *L50* (length of fish with 50% probability to escape through the grid conditioned it makes contact) and *SR* (= *L75-L25*).

The CLogit model was applied separately for each species in each grid section to model the size selection in the section. The value for the model parameters (*C, L50, SR*) was obtained were obtained using Maximum Likelihood (ML) estimation based on the experimental data pooled over hauls *i* (*1* to *h*) by minimizing:

$$-\sum_{i=1}^{h}\sum_{l}\left\{nE_{il} \times ln\left(\frac{C}{1.0 + exp\left(\frac{ln(2.0)}{SR} \times (l - L50)\right)}\right) + nR_{il} \times ln\left(1.0 - \frac{C}{1.0 + exp\left(\frac{ln(2.0)}{SR} \times (l - L50)\right)}\right)\right\}$$

(2)

Where nE_{li}, and nR_{li} are the number of individuals belonging to length class l in haul i that escaped in the grid section and got retained by it, respectively.

The goodness of fit diagnosis of the *CLogit* model to describe the experimental data was based on the p-value, model deviance vs. degrees of freedom, and inspection of the model curve's ability to reflect the trends in the data (Wileman et al., 1996). The ML estimation using equations (1) and (2) requires aggregation of the experimental data over hauls. This results in stronger data to estimate the average size selectivity, but it does not consider between-haul variation in selectivity (Fryer, 1991). To account for the effect of between-haul variation in the estimation of uncertainty in size selection and for the uncertainty in individual hauls due to sample sizes, we used a double bootstrap method (Millar, 1993; Herrmann, 2012). Based on the bootstrap results we estimated the Efron percentile confidence intervals (CIs) (Efron, 1982) for both the estimated parameters in equation (2) and the resulting size selection curve (1). We used the software tool SELNET (Herrmann et al., 2012) for the analysis and applied 1000 bootstrap iterations to estimate CIs.

Comparing size selection between grid sections

The difference in the size selection performance between the different grid sections were species-wise obtained by estimating the delta in size selection ($\Delta r(l) = r_1(l) - r_2(l)$). Where $r_1(l)$ and $r_2(l)$ represent the grid section size selection modelled by (1) for two different sections compared. 95% confidence bands for $\Delta r(l)$ was obtained based on the groups of bootstrap results for the individual sections by the method described in Larsen et al. (2018).

4.2.4. Results

Overview of experimental data

We carried out a total of 32 hauls between the 20th of February and 5th of March 2021 in the Southern Barents Sea (7118.03 - 7132.34 N / 02432.56 - 02551.97 E). During this experimental data collection period, a total of 14706 cod and 10358 haddock were caught and length-measured, and later included in the size selectivity analyses performed (Table 10).

Table 10: Overview of the hauls carried out with the three different grid sections tested during the experimental sea trials. The numbers of cod, haddock and redfish retained in the codend, cover over the grid (Cover I) and cover over the codend (Cover II) in each haul are provided.

Haul nr	Gear	Time	Trawl time	Depth	Cod			Haddock		
					Codend	Cover I	Cover II	Codend	Cover I	Cover II
1	2-panel grid	20:07:54	45	292.49	583	101	1	50	145	1
2	2-panel grid	00:09:25	50	290.97	1352	36	3	82	109	2
3	2-panel grid	18:45:12	47	291.65	1751	99	9	116	247	5
4	2-panel grid	09:49:29	44	298.41	431	71	4	66	298	23
5	2-panel grid	21:59:22	48	293.22	648	64	1	33	129	3
6	2-panel grid	03:28:02	31	305.90	457	67	3	52	141	3
7	2-panel grid	03:15:05	47	292.68	574	52	2	56	179	6
8	2-panel grid	06:24:18	35	296.9	355	56	1	63	188	10
9	2-panel grid	22:56:07	57	293.74	337	39	3	68	312	4
10	2-panel grid	02:39:02	40	294.14	167	16	3	69	230	2
11	4-panel grid	14:12:32	60	291.56	680	24	*	219	175	*
12	4-panel grid	17:53:04	37	289.76	423	16	*	90	175	*
13	4-panel grid	22:20:34	51	288.92	579	23	*	96	146	*
14	4-panel grid	02:24:54	44	284.55	394	11	*	117	158	*
15	4-panel grid	03:44:31	20	285.65	47	12	*	23	47	*
16	4-panel grid	04:49:02	41	287.15	120	11	*	48	132	*
17	4-panel grid	07:46:53	40	282.46	162	49	*	100	168	*
18	4-panel grid	09:53:06	59	283.51	157	36	*	141	194	*
19	4-panel grid	12:48:25	47	283.79	204	41	*	154	185	*
20	4-panel grid	14:20:08	60	286.29	62	26	*	109	161	*
21	4-panel grid mod.	05:18:00	60	284.31	570	58	*	207	225	*
22	4-panel grid mod.	09:25:47	36	286.19	587	66	*	272	257	*
23	4-panel grid mod.	13:44:00	41	289.59	96	12	*	206	146	*
24	4-panel grid mod.	16:05:04	32	285.91	106	14	*	103	105	*
25	4-panel grid mod.	18:08:06	54	285.87	363	38	*	203	305	*
26	4-panel grid mod.	22:03:33	61	286.56	418	28	*	161	194	*
27	4-panel grid mod.	01:52:09	60	289.05	351	22	*	131	193	*
28	4-panel grid mod.	05:14:02	59	285.04	632	82	*	307	321	*
29	4-panel grid mod.	09:26:57	61	287.75	276	22	*	151	167	*
30	4-panel grid mod.	13:35:04	60	283.73	176	25	*	156	211	*
31	4-panel grid mod.	16:45:02	80	288.00	255	18	*	153	235	*
32	4-panel grid mod.	18:47:07	92	287.07	111	17	*	255	364	*

Model fit and fit statistics

The results show that the *Clogit* model represented the selectivity data well in all cases, for all three gears tested and the two species included in the study (Fig. 25). In every case the p-value is >0.05, meaning that we cannot rule out that the difference between the model and the experimental observations is coincidental (Table 11).

For cod, the contact did not vary much between the three grid sections tested, and although it was lower approximately 5% lower for the 4-panel grid than for the other two configurations, the differences were not significant in any case. For haddock, the pattern was the same meaning that the 4-panel grid section resulted on a lower contact than the other two sections, but in this case the difference was approximately 10% and significant when the 2-panel and 4-panel grid sections were compared. For both species $L50_{grid}$ was considerably higher for the 2-panel grid section than the two different 4-panel sections tested and for both cod and haddock these differences were significant (Table 11).

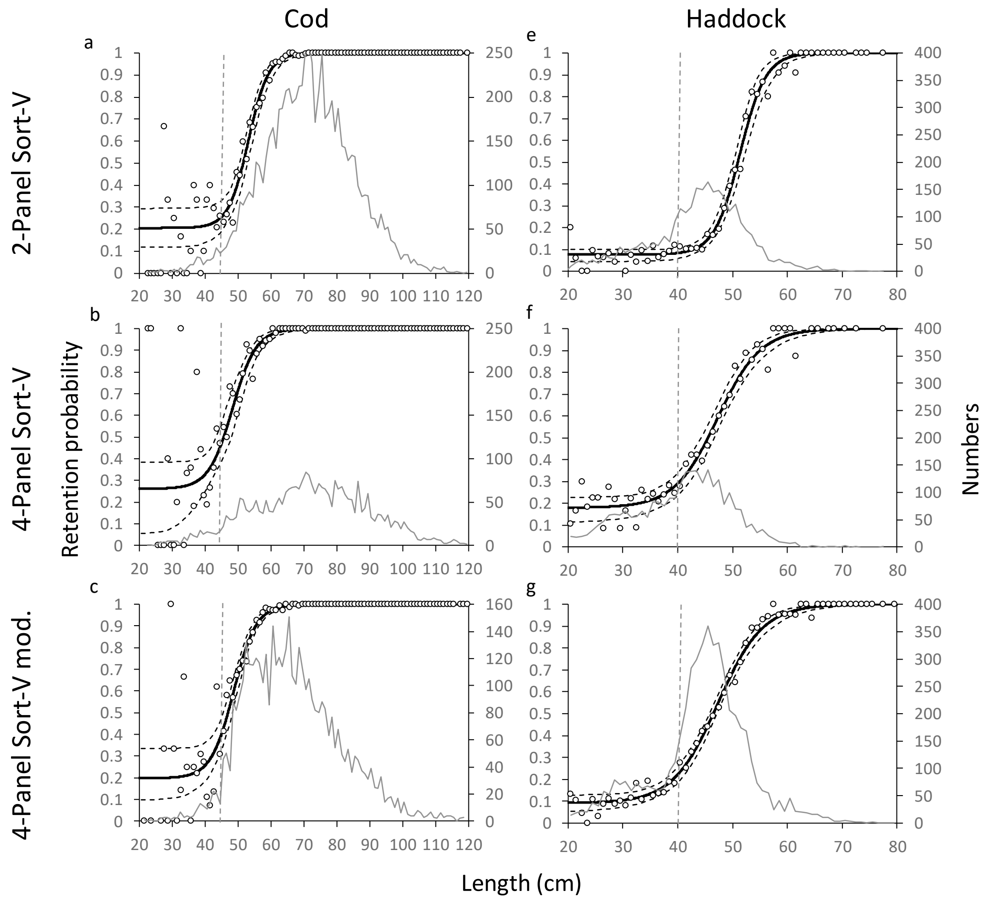


Figure 25: Length-dependent retention probabilities for cod, haddock and redfish with three different grid systems tested during the trials. The circles in each plot represent the experimental observations. The solid curve the represents the models fitted to the data. The stippled curves represent the 95 % CI's. The grey line represents the population fished by the gear (codend + cover (s)). The stippled vertical grey lines show the *MLS* for cod (44 cm), haddock (40 cm) and redfish (32 cm).

Table 11: Selection model, selectivity parameters and fit statistics for cod, haddock and redfish and the three grid section configurations tested during the sea trials.

Species	Grid section	C_{grid}	L50$_{grid}$	SR$_{grid}$	Deviance	DOF	P-Value
Cod	2-panel	0.79 (0.71 - 0.88)	53.15 (51.91 - 54.83)	6.70 (5.48 - 7.91)	62.64	97	0.9974
	4-panel	0.74 (0.61 - 0.95)	48.29 (44.88 - 51.13)	7.93 (5.77 - 10.78)	74.48	98	0.9632
	4-panel modified	0.80 (0.66 - 0.90)	48.67 (46.97 - 50.41)	7.57 (6.17 - 8.87)	51.49	93	0.9999
Haddock	2-panel	0.92 (0.90 - 0.95)	51.36 (50.57 - 52.22)	5.15 (4.26 - 6.22)	38.18	53	0.9376
	4-panel	0.82 (0.77 - 0.89)	47.27 (46.11 - 48.16)	8.63 (7.07 - 10.67)	41.93	46	0.6434
	4-panel modified	0.91 (0.87 - 0.95)	47.32 (46.58 - 47.95)	8.98 (7.62 - 10.66)	37.91	55	0.9618

Comparison of selectivity curves and delta plots

The results show that the 4-panel grid configuration leads to significantly higher retention rates of both cod and haddock than the 2-panel grid configuration (Fig 26a, c). This is also clearly illustrated by the delta plots (Fig 26b, d), which show that the 4-panel configuration leads to significantly higher retention of cod from 40 to 60 cm and significantly higher retention of haddock for all length classes between 20 and 54 cm than the 2-panel configuration. The difference between the sections is also length-dependent as the difference for larger cod and haddock is bigger than for the small (Fig. 26).

The comparison between the modified 4-panel configuration and the 2-panel configuration shows similar trends to the comparison between the 4-panel configuration and the 2-panel configuration. However, the differences in this case were slightly lower. The modified 4-panel grid configuration retained significantly more cod between 43 and 60 cm and more haddock between 35 and 53 cm than the 2-panel configuration. The difference in this case is also length-dependent as it is larger for the bigger cod and haddock (Fig. 27).

The results of the comparison between the standard and modified 4-panel grid configurations show that the former retains on average more cod and haddock between 20 and 55 cm. However, these differences were not significant for cod and only significant for undersized haddock (Fig. 28).

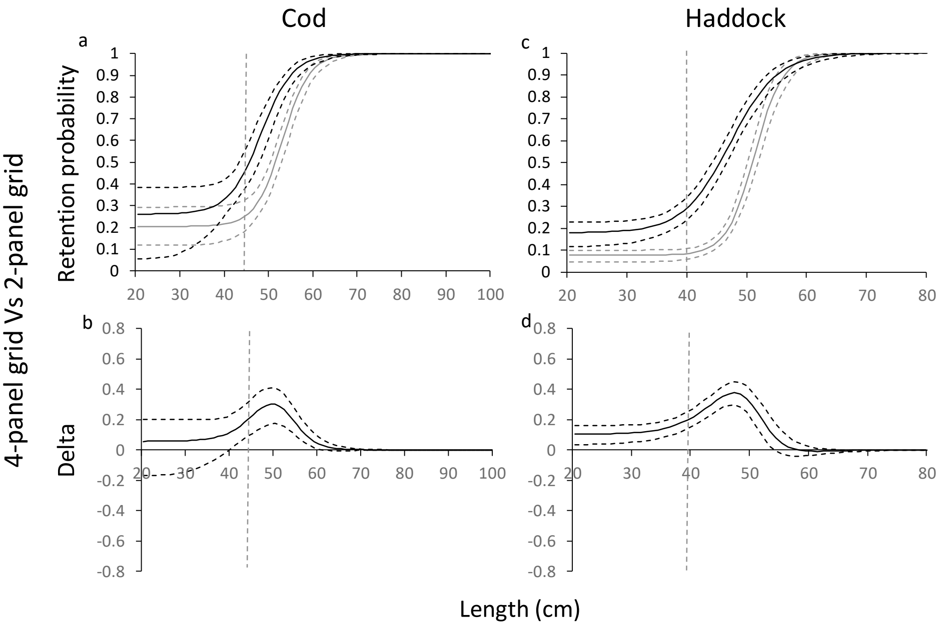


Figure 26: Comparison of the retention probability for the 4-panel (black) and 2-panel (grey, baseline) grid sections for cod (a) and haddock (c). Delta plots of the comparisons for the two species are shown in plots b, and d. The stippled curves represent the 95 % CI's in each case and the stippled vertical grey lines show the MLS for cod (44 cm) and haddock (40 cm), respectively.

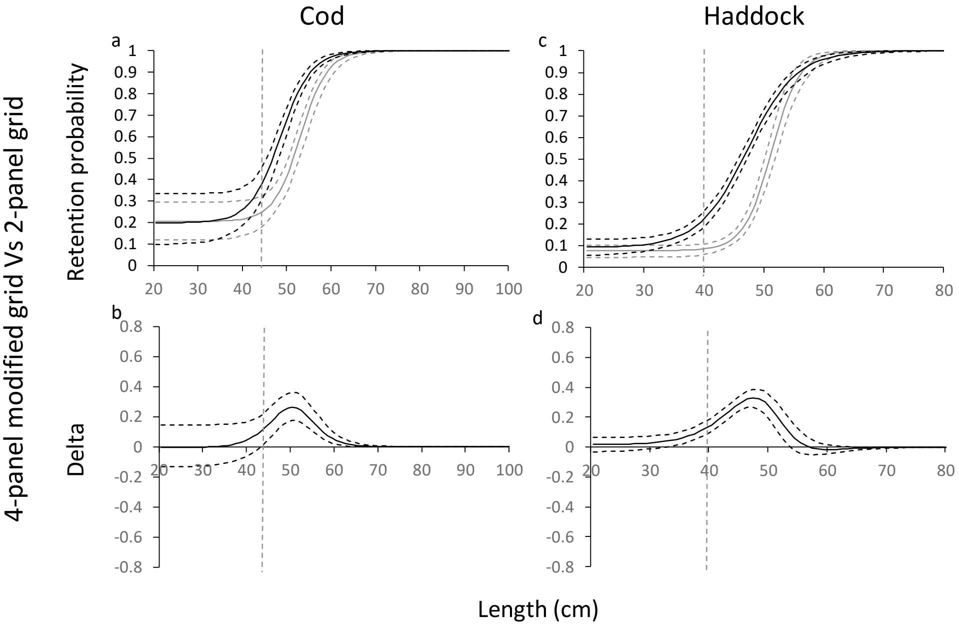


Figure 27: Comparison of the retention probability for the 4-panel grid section with the modified lifting panel (black) and the 2-panel grid (grey, baseline) sections for cod (a) and haddock (c). Delta plots of the comparisons for the two species are shown in plots b and d. The stippled curves represent the 95 % CI's in each case and the stippled vertical grey lines show the MLS for cod (44 cm) and haddock (40 cm), respectively.

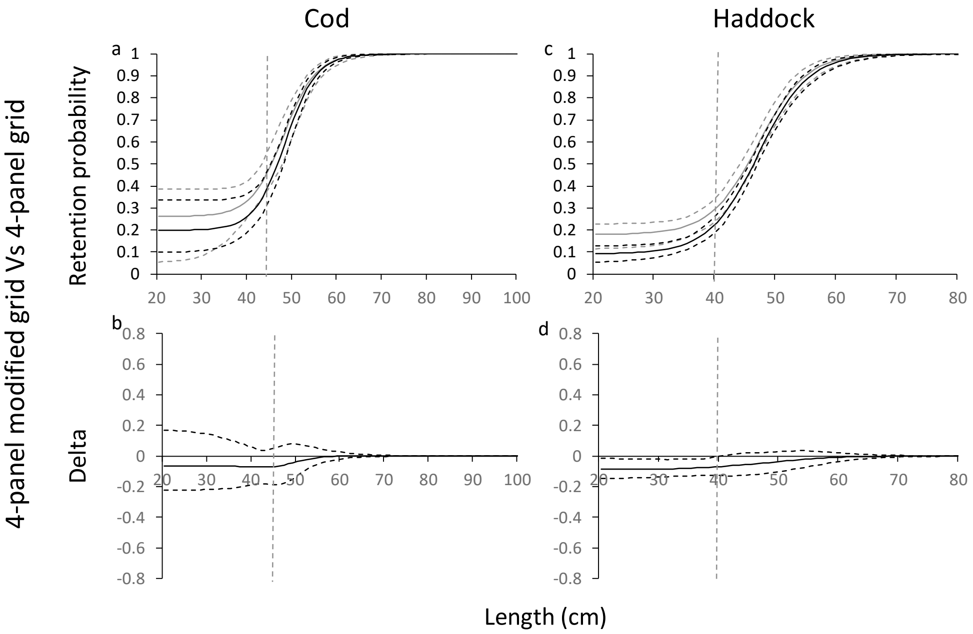


Figure 28: Comparison of the retention probability for the 4-panel grid section with the modified lifting panel (black) and the 4-panel grid (grey, baseline) sections for cod (a) and haddock (c). Delta plots of the comparisons for the two species are shown in plots b and d. The stippled curves represent the 95 % CI's in each case and the stippled vertical grey lines show the *MLS* for cod (44 cm) and haddock (40 cm), respectively.

4.2.5. Discussion

The 2-panel and 4-panel Sort-V sorting grid sections used in the Barents Sea are legal and a priori should have similar size selective properties. However, the results of the present study clearly show that this is not the case and that the modifications introduced to the 4-panel sort-V grid significantly change the selection properties of the grid despite the grid itself being identical in both cases.

One of the main sources for this difference is the difference in contact (Sistiaga et al., 2010), which provides an estimate of the fraction of fish that is subjected to a length-dependent sorting process at the grid, and is on average higher for both species and significantly higher for haddock when the 2-panel section configuration is used. Modifying the lifting panel in the 4-panel grid section improved the contact both species to levels similar to those observed with the 2-panel section configuration. However, the retention of both cod and haddock with the modified 4-panel grid configuration was still similar to that obtained with the standard 4-panel section and significantly different for a wide range of length classes to that obtained with the 2-

panel configuration. Therefore, it is clear that there are additional characteristics in the 4-panel configuration, which are different to those changed in the modified 4-panel configuration, that lead to that the retention is higher than in the 2-panel configuration for both species. Earlier studies have shown he importance of the lifting panel in sorting grid sections (Grimaldo et al., 2015), however, it is obvious that characteristics in the construction not necessarily linked to the lifting panel are creating a performance difference between the 2-and 4-panel grids.

In studies carried out with the flexigrid, which is the other legal grid system used in the Barents Sea today, Sistiaga et al. (2016) concluded that a 4-panel construction performed better than a 2-panel construction, a result that is opposite to the one obtained in the present study for the Sort-V grid system. However, Brinkhof et al. (2020) found the 2-panel flexigrid to perform substantially better than in Sistiaga et al. (2016), which adds uncertainty as to which of the two constructions performs better.

The present study shows that it is important to account for other design changes than simply the grid when evaluating the performance of a sorting grid system i.e. it demonstrates that the effect of section construction in the performance of the grid is important and need to be considered. Grids have earlier been claimed to be stable because they are rigid constructions, however, in this study substantially different results were obtained with grid sections where the grid itself was identical showing that the performance of grid sections can be sensitive to section configuration changes. Thus, effectiveness of the same grid when installed in different sections can provide significantly different results and performance regarding length-dependent release of fish.

4.3. Vertical separation of cod and haddock II

Inside the project group we discussed if the discouraging outcome from December 2020 could be a results of too short dividing panel. We therefore decided to repeat the experiments with a vertical panel along the full length of the trawl. We attached the panel along the seams (lastridges) to become a two-level Alfredo No. 3 design (Valdemarsen et al. 1985). We estimated the entrance of the panel was ca. 1.5 m above the fishing line. To reduce the risk for splitting or damaging the 22.3 m long vertical panel, we build it from several overlapping sections (see Fig. 29).

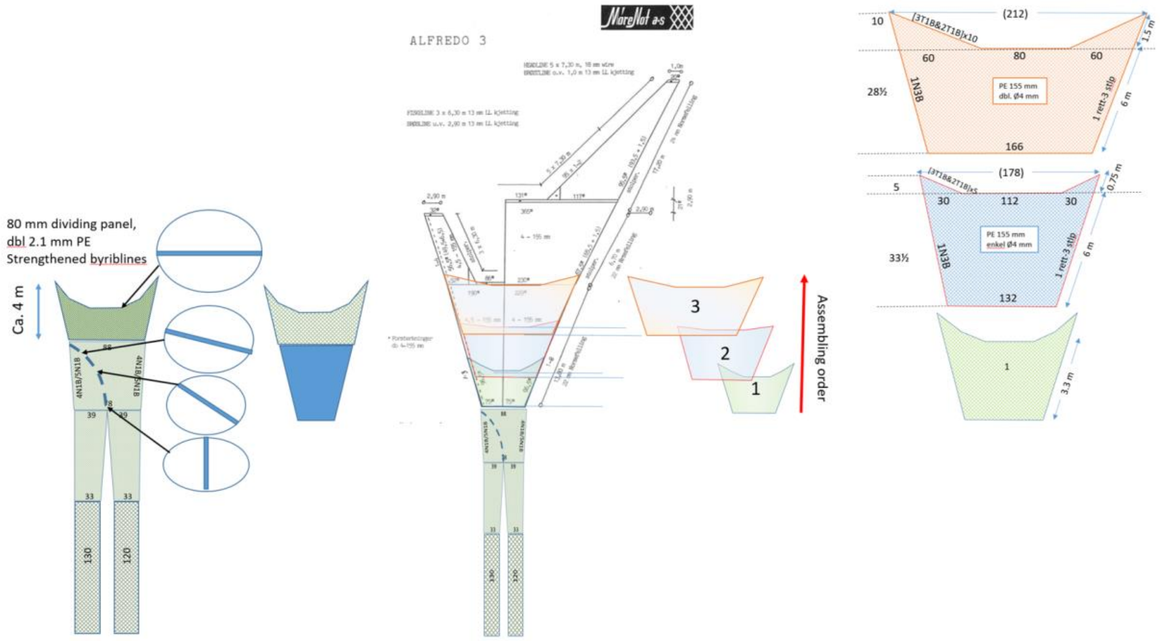


Fig. 29. The design of the two-level Alfredo No. 3 with full length of the vertical panel as tested March 2021.

Several observations (GoPro Hero 8) was made in natural light in depths from 70-80 m. The videos revealed that the entrance of panel was fully stretched, i.e. into a straight line. The aft end of panel three (front) and panel two had some excess of meshes when towing in shallow water and reduced door spread. We found in most cases very few fish on the shallow grounds, except from one haul where a sufficient sample of haddock was found. In this haul every haddock had entered the upper section of the trawl, while the lower section had a few relatively large cod and some

Fig. 30. Photo from one of the hauls in shallow water (80 m) and daylight where all haddock entered the upper section.

king crabs (see Fig. 30). During dark hours at night, the experiments were made at depths of 250-300 m. In these hauls we gained very similar results as in the December 2020 experiments. No measurements of fish were made since the obvious conclusion was that the system didn't work, except one single haul in shallow waters. The location used for observations in daylight is not representative for any commercial bottom trawl fishery in the Barents Sea. From these two periods it is fair to conclude that the technique tested (a vertical panel in a bottom fish trawl to separate species like cod and haddock) cannot be advised as a possible solution for optional use of a two-level trawl with codends with different mesh size to optimize the catch and size selectivity patterns for cod and haddock.

5. Final remarks and way forward

The results from the first three cruises carried out onboard the Research Vessel Helmer Hanssen in in the period December 2020 - March 2021 have contributed importantly to reducing some of the knowledge gaps in the Barents Sea gadoid fishery and answering some of the research questions posed in the project description (Sistiaga et al., 2020).

There is still substantial work left analyzing parts of the data collected and reporting all final results, and therefore it is not possible to draw final conclusions from all the cruises yet. However, the results presented here provide already with answers as to which ideas or concepts can be interesting to continue with the following phases of the project.

The results from the first cruise show that the grid sections imported from the Faeroe Islands which comprised of a plastic grid installed on a modified grid section, and that were was tested with bar spacings in 45 and 55 mm performed different to the Sort-V section that is compulsory in the fishery today. These differences were not significant for the 55 mm grid but they were significant for cod and haddock with the 45 mm grid. The data collected for the 45 mm grid were stronger than those collected with the 55 mm grid. The Faeroese grid retained significantly smaller fish, which could be partly attributed to the construction of the section and specifically the lifting panel. This could also be corroborated by underwater recordings, which showed that the lifting panel did not lead the fish towards the grid as well as in the steel grid sections. The concept of substituting the steel grid with a plastic/rubber grid in a Sort-V section is still interesting as it would solve several of the challenges (e.g. weight and maneuverability) of the existing grid concept. However, further work needs to be put into the development of a section, which could have as starting point a Sort-V system where the steel grid is substituted by an equivalent plastic grid and the floats removed.

Results also from this cruise showed that as expected, the retention of the 45 mm steel grid differed significantly from that of the 55 mm mandatory grid. The 45 mm grid retained more of the commercial sized fish. The extent of these differences is yet to be analyzed and we do not want to draw conclusions on the differences between these grids at this point. Further, fall through data on cod, haddock and redfish, which will allow predictions on the catch patterns expected for these three species with different bar spacing grids are yet to be analyzed. The results from these analyses will provide information as to whether or to which extent using different bar spacing grids in this fishery is appropriate.

Finally, the trials made during the first cruise with the horizontally divided trawl showed that cod and haddock had little or no preference for compartments and entered the upper and lower section and that the system did not work as intended. The modifications made during the third cruise, extending the separator panel towards the trawl mouth did not seem to improve the performance of the trawl and therefore, the obvious conclusion from the trials was that the system didn’t work. Therefore, and despite the success of this type of trawls in other areas like the North Sea, we suggest the experiments with this type of trawls in the present project are terminated.

The experiments with the short lastridge codends carried out during the cruise in January showed that this modification leads to increased mesh opening during the fishing process and that it can significantly improve the performance of diamond mesh codends. The qualities added to diamond mesh codends by shortening the lastridge ropes was further corroborated by the experiments in the third cruise, where the compulsory Sort-V sorting grid system was directly compared with a codend with shortened lastridges. The conclusion is that this type of codend has notorious advantages with respect to ordinary codends and that further experiments to determine issues like optimal reduction % in lastridges, choice of material and codend construction, and alterations with use need to be further investigated.

During the third cruise, we also compared the performance of a 2-panel Sort-V grid and a 4-panel Sort-V grid, to find out that the 4-panel configuration did not perform as well as the 2-panel configuration. Modifications of the lifting panel improved the performance of the 4-panel configuration, but it still did not perform as the 2-panel grid. These results show that grids are actually very sensitive to changes in the netting construction where they are installed, and that further research is required to discern what is the reason for the difference between these two grid configurations.

The results in this status report will be presented to the project group in the next group meeting (September 2021) and it is the group as a whole that will decide the focus of the activities for the autumn/spring cruises planned in the project. The results from the trials carried so far show that it is necessary to understand better the escape mechanisms involved in sorting grid systems (e.g. why do some specific fish escape and some other not, how do different constructions affect the performance of a grid that else is identical, etc.) to be able to improve the performance of potential new designs. Further work with devices that can potentially substitute or supplement sorting grids is still necessary. The work carried out with short lastridge codends so far is promising but further work with this type of codends and tests with other designs are still necessary.

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