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The Use of a Double Bottom Trawl Set to Assess the Selectivity of Innovative Codends in Baltic Cod (*Gadus morhua*) Fishing

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Abstract: The overall objective of the study presented in this paper was to evaluate the selectivity properties of three innovative codends in Baltic cod fishing: (1) an ultracross codend of 120 mm square mesh, (2) an ultracross codend with additional devices reducing the speed of water flow—one tarpaulin diffuser and one net confusor of 120 mm mesh, and (3) an ultracross codend with two tarpaulin diffusers and two net confusors of 120 mm mesh. These codends were firstly tested at sea by single trawls and compared to T90 and herring codend trawls, allowing assessment of caught fish mass and dimensions. Additionally, a special divided small-mesh coat for the innovative codends enabled determination of the amount as well as the length and mass of cod escaping from the codend both while the trawling gear was towed and while it was hauled. Further validation of codend selectivity was carried out by a double (twin) bottom trawl set deployed from one cutter in various variants of innovative codends compared to standard ones. The results of the study indicate that the use of an innovative ultracross codend and innovative devices reducing the water flow speed (tarpaulin diffusers and 120 mm net confusors) significantly reduces the number of undersized cod (<35 cm), even down to 1.3%, in the haul and contributes to a reduction in invisible mortal discard.

Keywords: Baltic fishery; selective fishing; bottom trawl design; ultracross codend; confusor; diffuser

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1. Introduction

The presented study concerns the application of a double (twin) bottom trawl set to assess the selectivity of innovative codends and the size (length and mass) of caught Baltic cod (*Gadus morhua*). As a result of increasing regulations, species and size selectivity, and bycatch restrictions, as well as the necessity to reduce fuel consumption and minimise ecosystem impact, bottom trawls used for commercial and scientific purposes have become increasingly complex in their design, material choice, and construction. The codend is the rearmost cylindrical part of the trawl connected to the narrow end of a tapered trawl net. Research dating back to the beginning of this century set as an objective the evaluation of the behaviour of different codend designs to provide information that is relevant for implementing technical management measures to improve fish selectivity and catch quality and to reduce energy consumption. Madsen et al. evaluated six different codend designs in 2015 [1]:

(1) A traditional diamond mesh codend;
(2) A T90 codend of European standard (meshes turned 90°);
(3) A Bacoma codend with diamond meshes in the lower panel and square meshes in the upper panel;
(4) A Bacoma codend with square meshes orientated in the T0 direction;
(5) A two-panel square mesh codend;
(6) A four-panel square mesh codend.

These codends were tested and assessed in a flume tank with a flow of 1.8 knots by a developed motion tracking system, and their drag was measured and compared. Other researchers studied the effect of the interaction of trawl warps, otterboards, and netting drag [2]; the effect of mesh size, twine material, and trawl gear accessories on the bottom trawl's hydrodynamic performance [3]; the capability of reducing towing drag by varying the shape and arrangement of floats and gear [4]; and the influence of gear design and catch mass on the fluid–structure interaction of a codend [5]

There were also studies regarding codend selectivity. Kynoch et al. studied the effect of strengthening bags on codend selectivity [6]; Nguyen et al. [7] developed a shaking codend that uses a mechanical stimulating device, which is an elliptical-shaped piece of polyvinyl chloride canvas attached to the posterior of a T90 codend that generates a lifting force with respect to drag, causing a 'shaking motion'. A shaking codend could stimulate fish movement and increase contact probability, both of which could increase the escape of small fish out of a codend, especially when combined with a codend design that maintains mesh openings. Frandsen et al. [8] studied selectivity and escapement behaviour of five commercial fishery species in standard square and diamond mesh codends. Demirci et al. researched the negative effect of an additional protective cover surrounding the codend on selectivity [9].

All of the abovementioned research was concentrated either on codend drag characteristics that are important for energy efficiency or on selectivity attained by a specific codend's mesh design. The construction of codends leading to slower water flow in such a way as to allow smaller fish to escape without harm has not been thoroughly studied so far. Also, although since the 1990s, a commercial twin trawl has significantly outperformed a single trawl for such fish as haddock (*Melanogrammus aeglefinus*) (by 22%), flatfish (*Pleuronectes platessa*) and lemon sole (*Microstomas kit*) (67%), anglerfish (*Lophius piscatorius*) (120%), and nephrops (*Nephrops norvegicus*) (421%) [10], its potential use for the scientific research of caught fish selectivity assessment has not been verified and implemented so far.

The above-described deficiencies in existing research on fish selective trawl gear influenced the authors of this paper to design and study innovative codends with such properties that enable undersized fish to escape without fatal harm. Such research is also of importance to future EU policy on bottom trawl fishing. A report by OCEANA [11] explores alternatives to Europe's bottom trawl fishing gear. In the transition away from bottom trawling, the socio-economic wellbeing of the people employed by trawl fleets needs to be ensured by designing and implementing effective and fair transition programmes. Innovative codends that help the preservation of cod, which interact with other Baltic species [12], could make such a transition more bearable. Questions of the future of Baltic fishing were raised in [13,14] and by the European Commission (EC) [15]. The EC proposed that the total allowable commercial catches (TAC) of cod in the Baltic Sea for 2024 should be further stopped (as they were in 2019–2023) for the Eastern Baltic and should be set to 24 tonnes only for the Western Baltic, following the recommendation of the International Council for the Exploration of the Seas (ICES).

The selectivity of cod fishing using innovative codends was the most important objective of the research carried out by the authors of this paper within two projects completed in (1) 2019–2022 and (2) 2023. A minor focus was also put on catch mass, size of fish that escaped while hauling, and trawl gear/codend drag. During the implementation of the first project, 70 scientific sea hauls were conducted using a single bottom trawl set prepared with various variants described in the "Materials and Methods" Section. During the implementation of the second project, 45 scientific sea hauls were carried out using a double (twin) bottom trawl set. A double (twin) bottom trawl set was used in 2023 to directly compare the performance of innovative codends with standard ones, whose selectivity had been previously evaluated only indirectly from single bottom trawls. The simultaneous trawling of an innovative codend and the standard one made it possible to statistically test and verify hypotheses of significant differences between these codends in mean percentage of caught undersized fish coming from the same population. A hypothesis can be also formulated: the use of innovative codends with devices reducing the water flow speed significantly reduces the number of undersized cod (<35 cm) in a catch comparing to traditional codend solutions.

2. Materials and Methods

Empirical research was conducted at full scale on real fishing boats (stern trawlers with a bottom trawl used for catching cod) using prototypes of innovative codends. The testbed was located in the Eastern Baltic coastal area forming traditional cod fishing grounds of Polish fishermen.

2.1. Fishing Boats, Codends, and Trawl Gear

Fishing boats used in the research (see Figure 1) were WŁA-187 and WŁA-220 in 2023 and WŁA-71 in 2019–2022, all operated by Necfish Co. from Władysławowo, Poland.

(**a**) (**b**) (**c**)

Figure 1. Fishing boats used in research (years 2019–2023): (**a**) WŁA-187, (**b**) WŁA-220, and (**c**) WŁA-71. Source: courtesy of Necfish Co.

The parameters of the fishing boats were as follows (see Table 1):

Table 1. Fishing boats' parameters.

Parameter	WŁA-187	WŁA-220	WŁA-71
Type	Cutter	Cutter	Cutter
Gross register tonnage (GT)	61	110	89
Length overall (LOA) [m]	19.09	20.55	22.20
Breadth [m]	5.80	6.00	6.01
Design draught [m]	2.63	2.55	2.20
Engine type	four-stroke, MDO	four-stroke, MDO	four-stroke, MDO
Maximum continuous rating [kW]	294	368	289

Each trawler was equipped with two hydraulic net winches at the stern. They also had a sonar cable winch and two auxiliary electric winches.

Two types of innovative codend of 120 mm mesh for a Baltic cod (single-species) fishery, minimising the bycatch of much smaller herring (*Clupea harengus*) and sprat (*Sprattus sprattus*), were designed, constructed, and analysed hydrodynamically, and their selectivity was compared with an ultracross codend of 120 mm square mesh (UC), a standard EU codend for cod fishery (T90 codends), a herring codend, and between themselves. They were named by the following acronyms:

(1) UC + JD + JK: a UC with innovative devices reducing the speed of water flow, i.e., one tarpaulin diffuser—JD and one net confusor—JK,
(2) UC + DD + DK: a UC with innovative devices reducing the speed of water flow, i.e., two tarpaulin diffusers—DD and two net confusors—DK (see the photos in Figure 2).

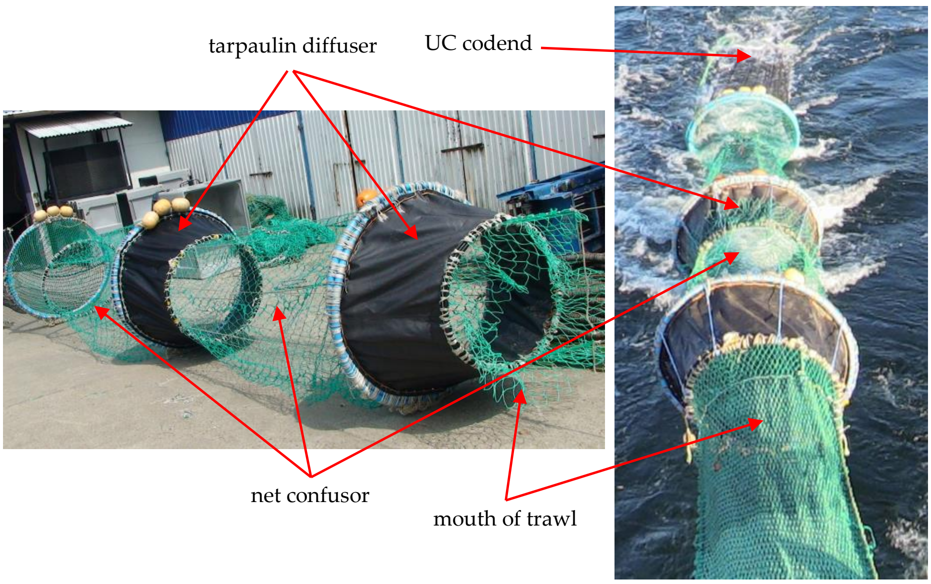


Figure 2. UC + DD + DK codend stretched out before sea trials and while hauling.

Additionally, in 2019, several single bottom trawls were conducted with an extra-fine mesh codend cover installed for the collection of escaping fish. The acronym of the cover was set to DOD.

Measurements of the geometry of the codends were made by means of a specifically designed hydroacoustic system, which measured the distance between 10 pairs of ultrasonic transducers fixed to the codend's net fabric. The measurement range of the system was from 0.1 m to 10 m, with a measurement accuracy of 1 cm. The measurement frequency was 1 Hz.

An example of how the transducers were installed is shown in the photo presented in Figure 3, which includes an explanation of the fastenings.

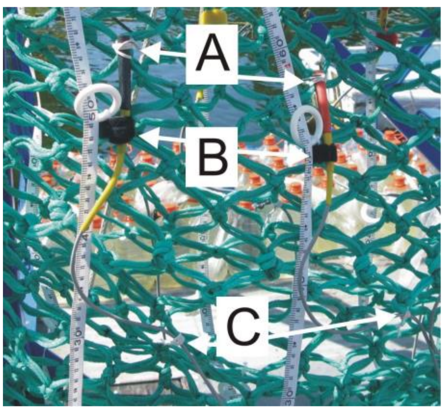


Figure 3. The net of a tested codend with ultrasonic transducers installed (black transmitter, red receiver) with (**A**,**C**)—permanent fastenings to the net fabric; (**B**)—pass-through fastening.

The extra DOD for a tested codend (see Figure 4), its rigging, the trawl doors, and the trawl lines (warps, sweeps, and bridles) were arranged to be released and retrieved from the cutter's stern by a trawl winch. The sweeps, bridles, and the body of the trawl, along with elements of its armament, were wound onto the net winch. Due to the use of large hoops for spreading the codend's cover, the cover was retrieved manually. Emptying the codend, the divided cover, and its inner sleeve of caught cod was carried out by packing. "Packages" of caught cod were hoisted via a lifting strap (halving becket), using a rope wound on the sliding drum (capstan) of the trawl winch.

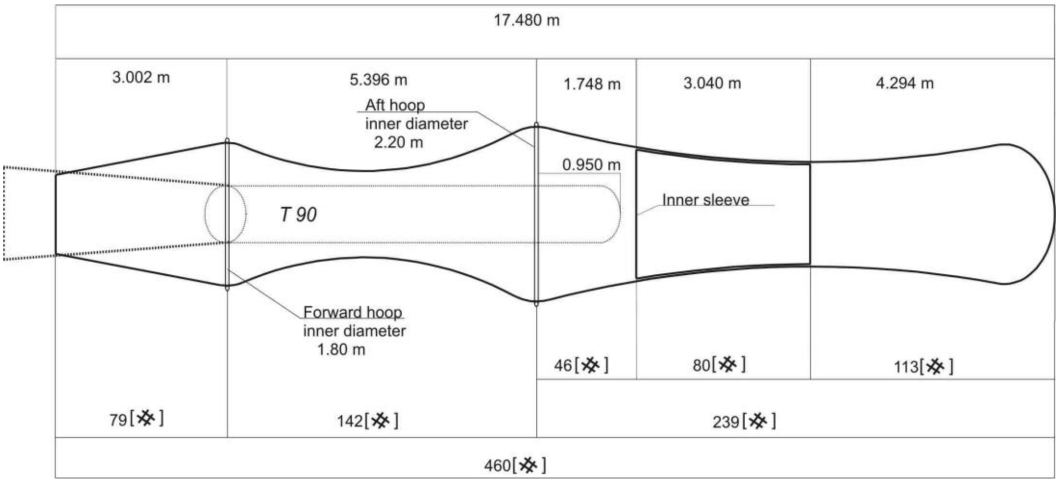


Figure 4. DOD cover applied to a T90 codend.

An exemplar bottom trawl had the following parameters (see Figure 5):

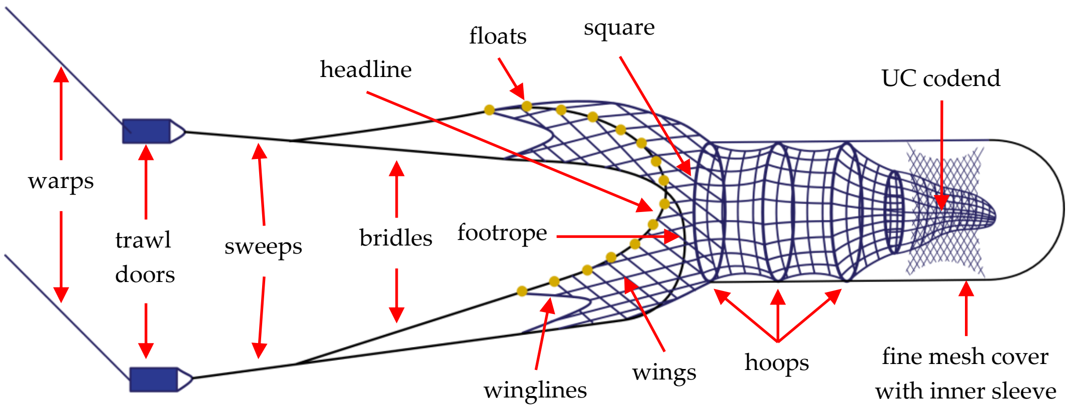


Figure 5. Construction of the single bottom trawl set with a tested innovative codend and its cover.

- Trawling ropes (warps): steel wire rope of diameter 16 mm and length 300 m;
- Bottom trawl doors of type Thyboron 84″;
- Sweeps: steel wire rope of diameter 14 mm, with rubber rings and length 110 m;
- Bridles: steel wire rope, diameter 14 mm, with rubber rings, 2 × 25 m;
- Length of the trawl body (wings + square + mouth): 50 m;
- Flotation of the headline: 40 plastic floats, diameter 200 mm;
- Footrope: steel rope of diameter 12 mm with rubber pulleys + 26 pieces of plastic rollers of diameter 200 mm;
- Spacing of trawl doors: approx. 75 m (rescaled from measurements by underwater camera during a testbed of prototype trawl gear with a five-times-smaller codend in 2018);
- Vertical spacing in the middle of the headline: approx. 3.5 m;
- Drag of the trawl set at a towing speed of 3 knots: approx. 22 kN.

2.2. Research Testbed and Scientific Hauls (Runs)

The research fishing was conducted in traditional cod fishing grounds of Polish fishermen located north-east of Władysławowo harbour, i.e., in the ICES area 27.3.d.26 (South-Eastern Baltic) comprising Polish administrative fishing squares R7, R8, S7, and S8 (see Figure 6) at depths ranging from 44 m to 90 m. The duration of one trawl was 1 h (from the end of running out the trawl set to the start of retrieval) with a trawling speed of approximately 3 knots (1.5 m/s).

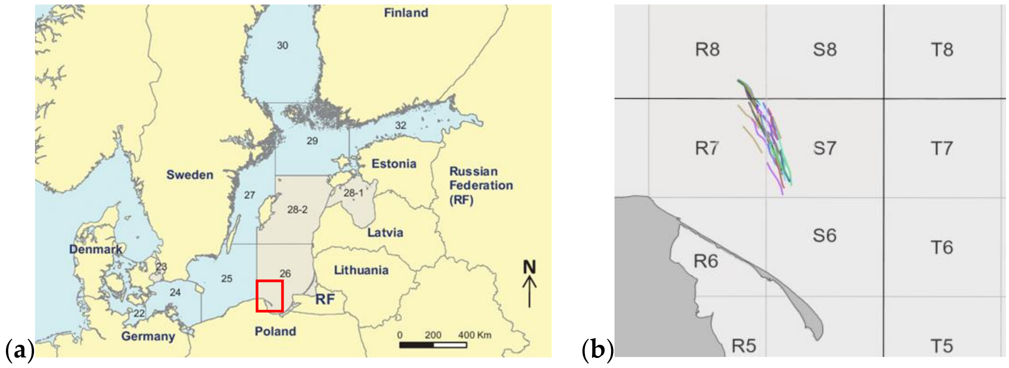


Figure 6. (**a**) The research in ICES area 27.d.26 marked in red (source of chart: ICES public domain); (**b**) recorded positions of scientific hauls performed in 2023 plotted on zoomed area of red outline with Polish administrative fishing squares drawn.

The following hauls were performed in particular years (as the experimental part of the research programme):

- *2019:*

Some 70 hauls in the area marked red in Figure 7 in months May to August using a single bottom trawl set with various variants. They comprised:

(1) 20 hauls of codend variant: UC + DD + DK;
(2) 10 hauls of variant: T90 + DD + DK;
(3) 2 hauls of variant: herring codend + DD + DK;
(4) 8 hauls of variant: T90;
(5) 10 hauls of variant: UC + DD + DK + DOD;
(6) 10 hauls of variant: UC + JD + JK + DOD;
(7) 10 hauls of variant: UC + JD + JK.

- *2020:*

Some 40 hauls in the same area in months June to August using a single bottom trawl set with various variants. They comprised:

(1) 20 hauls of codend variant: UC;
(2) 20 hauls of codend variant: T90 + JD + JK.

- *2021:*

Some 30 hauls in the mentioned area in July and August using a single bottom trawl set with various variants. They comprised:

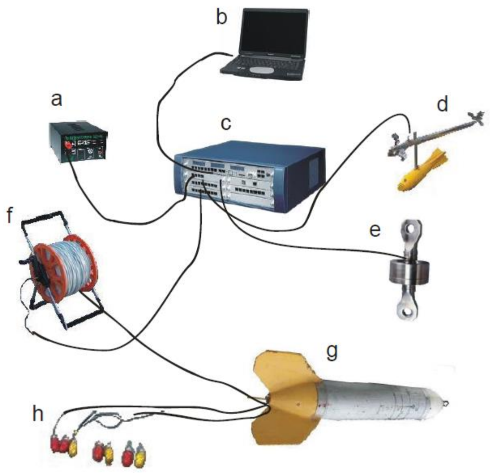
(1) 15 hauls of codend variant: UC + JD + JK;
(2) 15 hauls of variant: T90.

- *2023:*

Some 45 hauls in the mentioned area in the period of June to August, using a double (twin) bottom trawl set with various variants. They comprised:

(1) 10 hauls of codend variant: starboard trawl set—T90 and port trawl set—UC + DD + DK;

(2) 10 hauls of variant: starboard trawl set—herring codend and port trawl set—UC + DD + DK;
(3) 10 hauls of variant: starboard trawl set—herring codend and port trawl set—UC + JD + JK;
(4) 10 hauls of variant: starboard trawl set—herring codend and port trawl set—UC;
(5) 5 hauls of variant: starboard trawl set—T90 codend and port trawl set—herring codend.



a—power supply;
b—on-board computer;
c—on-board control unit;
d—log;
e—force gauge;
f—cable line;
g—underwater control unit;
h—ultrasonic transducers (red—receivers, yellow—transmitters).

Figure 7. Hydroacoustic system for measurements of trawl set drag.

In November 2023, an additional 5 hauls were carried out using a standard bottom trawl set with a T90 codend to assess fishing boats' energy consumption while trawling and to gather data for building their digital twins in a full mission ship's bridge simulator.

2.3. Measurements of Drag

Measurements of the drag of trawl sets were performed by a specifically designed hydroacoustic system (see Figure 7). This recorded measurement data collected in real time from several spatially distributed sensors in the trawl sets and derived the trawl sets' drag.

2.4. Measurements of a Catch and Operation of a Codend Cover

Representative samples of fish from the entire trawl, depending on the catch amounts obtained, were measured in terms of length (cm) and mass (kg):

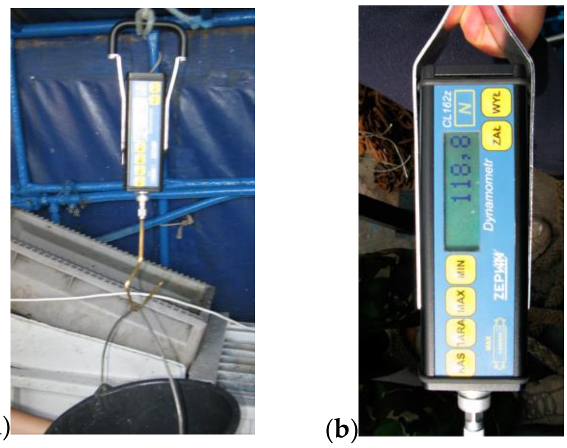
- Lengths of individual cod;
- The mass of individual cod and the collective mass.

The caught cod underwent a preliminary selection while being removed from the water. During trawls with a codend cover (DOD) in 2019, the codend and the DOD that had collected the fish which managed to escape were retrieved to the cutter's deck separately. Firstly, cod were removed from the codend, which had been retrieved through a special zipper sewn into the cover. Secondly, the fish were removed from the cover, i.e., individuals escaping the codend during towing, which accumulated in the end part of the cover. Finally, the cover's inner sleeve was hoisted to the deck and the fish escaping the codend during hauling were removed. The three assortments of fish obtained in this way, and separated from each other, were placed in separate and labelled boxes. The boxes were marked by a different colour, e.g., cod retained in the codend—red boxes, cod that escaped during trawling (fish from the divided cover)—green boxes, and cod that escaped during hauling (fish from the inner sleeve)—white boxes.

If the catch was too large to be measured in its entirety, a sampling method was used. Fish were sampled by means of a bucket in order to prevent subjective selection of only larger fish by hand, for example. To take a representative sample, usually 2 boxes (approx. 200 pieces, 60 kg) of cod from each batch were randomly collected. In total, 6 boxes of cod were collected from each haul. The remaining fish that were not included in the sample were sorted into large and undersized fish. After sorting, they were weighed together, which enabled data to be obtained on the mass of large and undersized fish in the bag, cover, and sleeve from each haul separately. Measurements took place on board the ship between successive trawls if the weather permitted. Otherwise, the fish were weighed and measured after mooring at the quay or at the fishermen's base.

For weight measurements, a CL162Z electronic force gauge [16] (see Figure 8), designed to measure compressive and tensile forces up to a maximum of 1kN, was used. The force gauge had a tare function and functions of freezing the displayed result and displaying the maximum and minimum values. The force gauge was equipped with an RS232 serial communication link that allowed measurement results to be transmitted to a computer where they were converted to mass [kg]. Characteristics of the force gauge were as follows:

- Measurement range 0–1000 N;
- Overload capacity max. 50% of the measurement range;
- Maximum relative measurement error < 0.0015%;
- Minimum single measurement time 0.2 s.



(a) (b)

Figure 8. (**a**) The electronic force gauge used in the research and (**b**) its readout.

To measure the length of the caught fish, an innovative solution was developed by the authors of this project, which involved the use of a precise laser rangefinder manufactured by Leica Geosystems, type DISTO a6 [17]. The device supported data transmission using Bluetooth technology, which enabled wireless communication with a computer to record measurement data via dedicated software. The rangefinder was characterised by the following parameters: accuracy $\pm$ 1.5 mm, distance measured from 0.05 to 200 m, and resolution (displayed unit) of 1 mm. The measurement stations are shown in Figure 9, where:

(a) The station for measuring the length and weight of the caught cod with a DISTO laser rangefinder mounted on a movable guide and a CL162Z electronic force gauge;
(b) The station for data recording on a portable tablet or laptop.

Carpentry tables and appropriately prepared plastic boards were used to build the measurement stations. A laser rangefinder was fixed to a movable guide made of stainless steel. Additional control over the length measurements was provided by a permanently attached scale—a metal measuring tape. Thanks to the use of durable stainless steel and plastic elements, these stations were durable and resistant to seawater. Additionally, they were easy to keep clean. The devices used in measurements had their own power sources, which greatly facilitated their operation in marine conditions. The data were recorded in ASCII format, which is easily convertible to Excel or other software for numerical data analysis. Once the data had been entered into the computer, the measured cod were divided into sized and undersized. Then, the measured cod from the samples were categorised into 1 cm length classes. The data collected in this way were further processed to describe the final results. To obtain full information on the biomass of the fish caught in the entire haul, the mass of the cod from the samples was added to the mass of the cod from the general measurement (the fish that were not included in the sample and not weighed individually). Mature-sized (≥35 cm) and undersized fish from the samples were added to the sized and undersized cod sorted by the ship's crew as well.

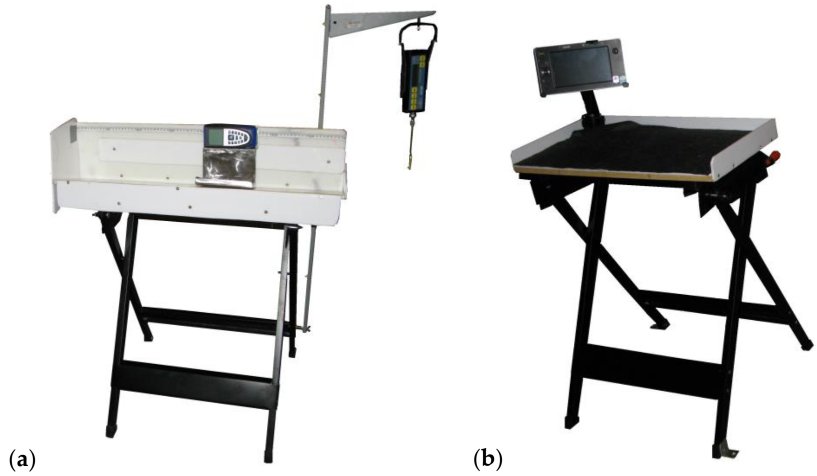


Figure 9. The measurement stations: (**a**) for length and weight of fish; (**b**) for data recording.

Additionally, to control the process of closing the inner sleeve of the codend's cover, it was necessary to continuously measure the force tensioning the rope closing the sleeve. For this purpose, a specially constructed portable station was used, accommodating a precise force gauge and three rollers attached to the frame through which the rope closing the sleeve passed. A station in the form of a three-roller with a CL162Z electronic force gauge for measuring forces in the line closing the sleeve is presented in Figure 10.

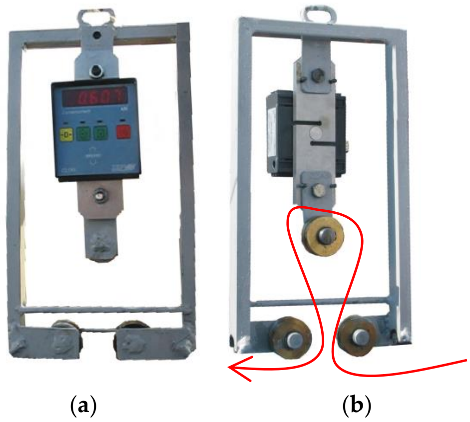


Figure 10. The station for measuring tension of the line closing the sleeve: (**a**) front view; (**b**) rear view.

The rope closing the cover's inner sleeve was pulled in using a prototype, autonomous, combustion-driven winch installed onboard Necfish cutters (see the photo in Figure 11). This winch was permanently attached to the deck in the stern part.

The fine-mesh cover designed to assess the selectivity of codends was made sure to be properly adjusted and armed, and it was tailored to the specific codend and fishing vessel before it was used in the research at sea. The cover towed on a single trawl line was to be properly rigged (taking its load and floatation into account) so that it did not rotate around its axis while in motion. It was especially important to choose a lanyard stopper (twine connector) of such a thickness that it would be torn off before starting the process of closing the sleeve located inside the cover. This way, the inner sleeve could separate the fish leaving the codend during the phase of towing the trawl set from the fish leaving the codend while hauling in the trawl set on board the cutter. A graph of the process of closing the sleeve is shown in Figures 12 and 13, along with the visible moment of breaking the twine connector and tightening the sleeve after approximately 100 s.

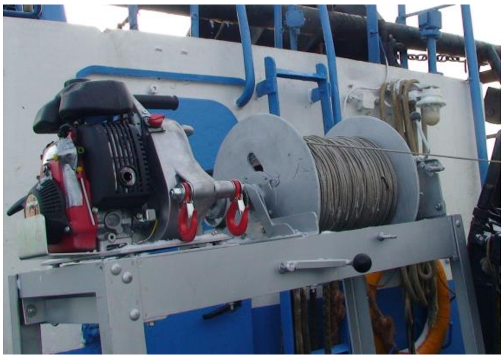


Figure 11. The winch used for closing the sleeve of codend cover.

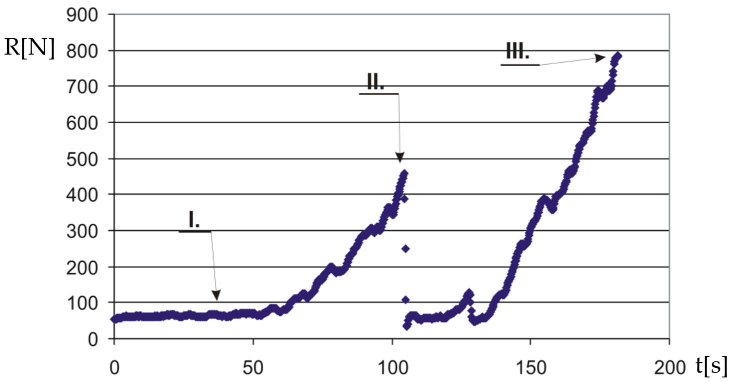


Figure 12. Forces on the rope closing the inner sleeve of the codend's divided cover.

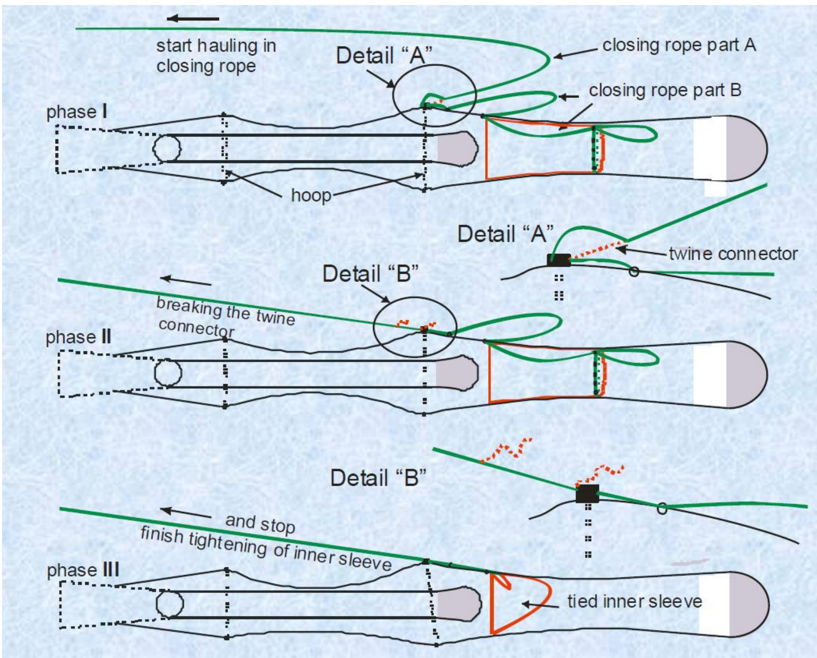


Figure 13. Phases of the codend's cover inner sleeve tightening.

Looking at Figures 12 and 13, in phase I, the rope closing the inner sleeve of the cover is pulled in. One can see that the tension force on the rope begins to increase. This proves that the stopper (twine connector) is being tightened, and it breaks after about 100 s, when the tensioning force drops rapidly (phase II). In the next stage, the drag begins to increase again, which indicates that the inner sleeve in the fine-mesh divided cover is closing. When the drag value increases to approximately 800–1000 N, then the inner sleeve has been tightly closed—this guarantees the separation of fish that will start to leave the codend in the process of hauling the trawl set from those that left it earlier, i.e., during towing. The retrieving time depends on the length of the closing rope and the speed of pulling in. Therefore, the moment of breaking the stopper and closing the sleeve should be determined on the basis of the force gauge readings.

The length of the twine connector, determined empirically to fit the breaking force of approx. 500 N, was set to 30–35 cm long. Its ends should be permanently tied to the codend closing rope and to the cover hoop, in the vicinity of the clamping jaw used. This is illustrated by the underwater photo in Figure 14.

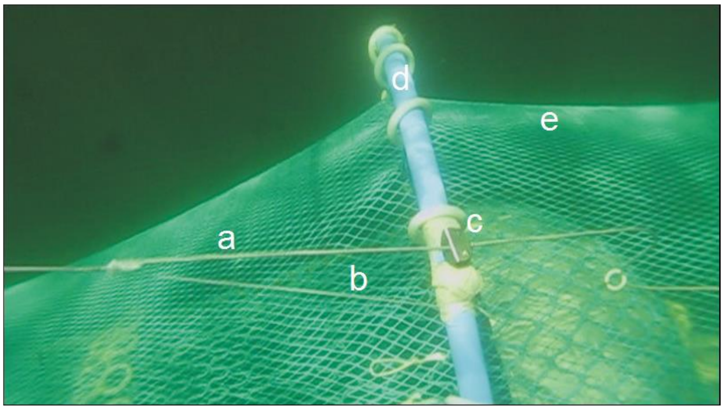


Figure 14. Arrangement of the cover's inner sleeve closing: a—closing rope, b—stopper, c—clamping jaw (cleat), d—plastic ring, and e—fine-mesh DOD of a codend.

2.5. Statistical Testing of Differences in Catches among Codends

A box and whisker plot was used to present selectivity in terms of the mass of a catch and % of undersized cod graphically.

The Microsoft macro package Analysis ToolPak in Excel 365 was used for statistical testing with its *t*-test for two-sample testing assuming unequal variances (also referred to as a homoscedastic *t*-test). Particular codends were thus compared in pairs for selectivity in terms of % of undersized cod. The null hypothesis was that both means were equal (mean selectivity for two codends, $m_1 = m_2$ or $(m_1 - m_2) = 0$, where m_1 was taken for an innovative or likely more selective codend whose sample data are input first into Analysis ToolPak, i.e., data with a lower mean). The alternative 'one-sided' hypothesis was that both means were different in that $m_1 < m_2$ or $(m_1 - m_2) < 0$, as the lower mean is better in view of the selectivity definition.

Correlation coefficients of Pearson and Spearman were used to assess how closely two variables of undersized cod percentages, obtained from double bottom trawls with the most selective codend and non-selective one, co-vary.

The distribution of cod lengths in the research area acquired from catches by non-selective herring codends in 2023 was fitted to a probability density function (PDF) using scripts created in Mathworks Matlab® 2023 with Curve Fitting Toolbox 3.9.

3. Results

The quantitative results of the study have been categorised into three researched topics: (1) assessment of cod quantity that escaped while hauling the trawl; (2) estimation of innovative codends' drag; and, as a major focus, (3) selectivity and cod length structure. Not all of the planned hauls in years 2019–2021 were conducted successfully, mainly due to several technical problems with the specifically designed codend cover (DOD) or twisted confusors and the administrative limit set to scientific fishing (scientific fishing was allowed by the Polish ministry responsible for fisheries up to the limit of 12,600 kg for 50 hauls a year).

3.1. Assessment of Cod Quantity That Escaped While Hauling the Trawl

The use of a DOD allowed the separate assessment of the number of cod leaving the codend when hauling the trawl. Such an assessment was motivated by the fact that the cod which escaped during retrieval without proper slowing of hauling speed would have their swim bladders damaged due to fast decompression and would die [8,11]. Research carried out on 20 hauls with a DOD (variants 2019 no. 5 and 6) showed that 36% of cod escaped during hauling, which constitutes approximately 31% of the catch mass as an invisible discard if they sustained mortal wounds during the process (see Table 2). The standard deviation (SD) resulting from variance among hauls was approximately 5½ percentage points.

Table 2. Percentages of cod which escaped during hauling codends with DOD in 2019 (20 hauls).

Haul No.	Number of Caught Cod	Mass of Caught Cod [kg]	Number of Cod Which Escaped during Hauling	Mass of Escaped Cod [kg]	Escaped Cod %	Escaped Cod % of Catch Mass
1	50	48.9	25	20.5	33	29.5
2	129	100	74	60.3	36.5	37.6
3	121	105	53	40.2	30.5	27.7
4	35	33.6	15	12.5	30.3	27.1
5	49	52.8	29	20.8	36.9	28.3
6	88	80.7	74	58.2	45.7	41.9
7	32	38.25	15	11.3	31.5	22.8
8	100	90	56	40.3	35.7	30.9
9	28	34	28	21.2	50	38.4
10	44	37.75	30	18.3	40.6	32.6
11	85	99.9	46	40.5	35.2	28.8
12	74	67.55	38	22.3	34	24.8
13	112	95.25	55	42.8	32.8	31.0
14	70	65.95	41	33.2	37.1	33.5
15	62	57.5	29	20.4	32	26.2
16	64	62.95	39	29.4	38	31.8
17	180	174.85	81	78.2	31.1	30.9
18	67	65.9	31	26.5	31.9	28.7
19	50	41.65	40	27.1	44.5	39.4
20	68	80	34	25.5	33.3	24.2
Sum	1508	1432.5		**Mean**	**36.0**	**30.8**
				SD	**5.4**	**5.2**

The obtained results shed new light on the level of fishing mortality and indicate the urgent need for an approach to the problem of selectivity in trawl fishing of Baltic cod, taking into account both selective codend solutions and trawl hauling procedures.

3.2. Estimation of Innovative Codends' Drag

The economic aspects of trawling with innovative codends were not the main part of this research, and thorough analysis of drag, fuel consumption, energy efficiency, and the optimisation of resultant emissions should be further undertaken in future studies. Nevertheless, a potential increased resistance of trawls with innovative codends has been assessed by drag measurements of T90, UC + JD + JK, and UC + DD + DK trawl sets while towing with speeds in the range of 1 to 1.9 m/s (see Figure 15).

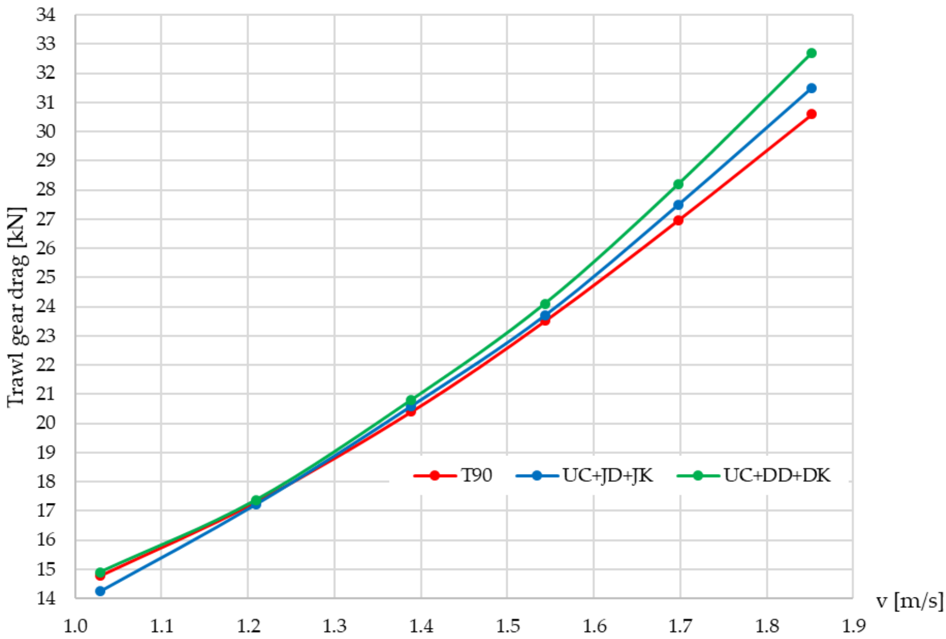


Figure 15. The drag of three variations of trawl sets with codends T90, UC + JD + JK, and UC + DD + DK.

It can be noticed that for a towing speed of 1.5 m/s (approximately 3 kts) used in cod bottom trawling, the drag of a trawl set with an empty T90 codend was about 22.5 kN, the drag of a trawl set with a UC + JD + JK codend was about 22.7 kN, and the drag of a trawl set with a UC + DD + DK codend was about 23 kN. The difference between the extreme drag values is less than 2.2%. These values are consistent with [1], as the drag of the codend itself is relatively small and amounts to approximately 2–3% of the total drag of the whole stern trawl gear, depending on whether it is empty or full. Also, because the drag of the T90 codend is up to 3% greater in comparison to the ultracross Bacoma type (which was measured in [1]), the drag of the innovative codends constructed of ultracross net was only insignificantly higher than T90's one. The innovative devices reducing the speed of water flow contributed to the growth of the resistance value while simultaneously the net of ultracross mesh contributed to its decline in comparison to T90. And it is worth noting that on the scale of actual measurements of the entire trawl set, the differences in drag are within the limits of measurement accuracy.

3.3. Selectivity and Cod Length Structure

During research in 2019, 7891 kg of cod was caught in trawls, of which the lengths of 12,757 cod were measured, the mass of which equalled 5965 kg. During research in 2020, 3850 kg of cod was caught in trawls, of which the lengths of 3509 cod were measured, the mass of which equalled 2222 kg. During research in 2021, 3319 kg of cod was caught in trawls, of which the lengths of 2593 cod were measured, the mass of which equalled 1595 kg. During research in 2023, 11,047 kg of cod was caught in trawls, of which the lengths of 9406 cod were measured, the mass of which equalled 2685 kg. The main reason for the difference in measured cod mass in relation to their number observed in 2023 (average mass 285 g) was largely the non-selective catch of undersized cod by the herring codend used comparatively in double bottom trawling.

Figures 16–18 show statistics of the percentage of undersized cod number (<35 cm) and of mass of cod in one haul using various codends with and without innovative devices in the years 2019–2023.

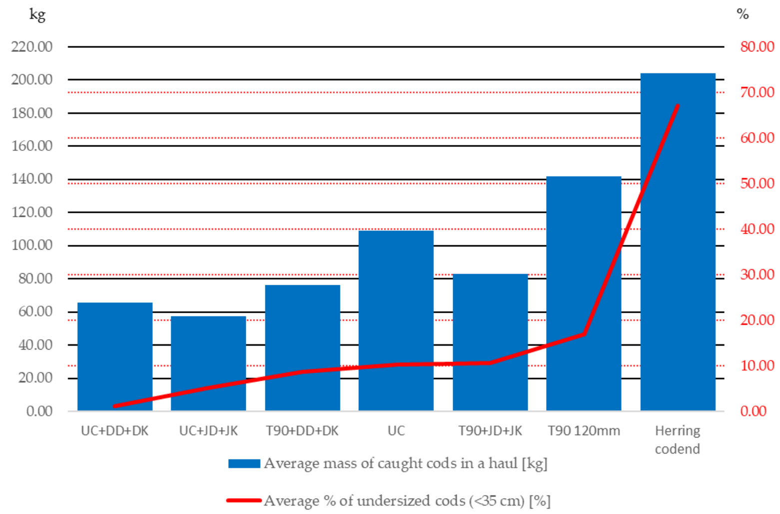


Figure 16. The percentage of undersized cod (<35 cm) and the average mass of cod in one haul in years 2019–2023.

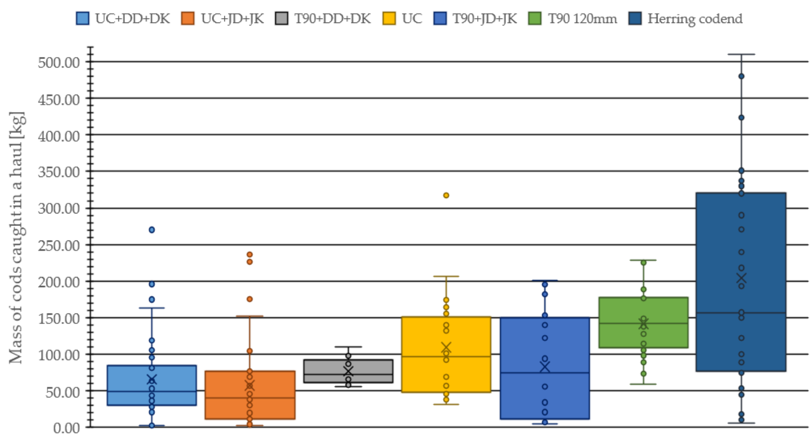


Figure 17. A box and whisker plot of mass of cod in one haul in years 2019–2023.

In Figure 16, the means are shown for both catch mass (blue columns refer to the left vertical axis) and selectivity % (red line refers to the right vertical axis) in one haul. The average percentages of undersized cod which were caught using various codend variants were as follows:

(1) UC + DD + DK: 1.2% ± 0.9% (SD);
(2) UC + JD + JK: 5.1% ± 2.9% (SD);
(3) T90 + DD + DK: 8.7% ± 5.3% (SD);
(4) UC: 10.4% ± 2.9% (SD);
(5) T90 + JD + JK: 10.7% ± 4.3% (SD);
(6) T90: 17.0% ± 6.2% (SD);
(7) Herring codend: 67.0% ± 12.6% (SD).

In the box and whisker plots in Figures 17 and 18, the left and right sides of each box are the lower and upper quartiles. The box covers the interquartile interval, where 50% of the data are found. The horizontal line that splits the box in two is the median. The mean is indicated by a cross. The whiskers are the two lines outside the box that go from the minimum to the lower quartile (the start of the box) and then from the upper quartile (the end of the box) to the maximum. A variation of the box and whisker plot restricts the length of the whiskers to a maximum of 1.5 times the interquartile range. The data outside this range are outliers. All distributions except the mass of cod in the herring codend and the percentage of undersized cod in the UC codend are approximately symmetric, because both half-boxes of the bottom and top side of the median are almost the same length. The most concentrated distribution is for the percentage of undersized cod in the UC + DD + DK codend, which is also confirmed by the lowest SD value.

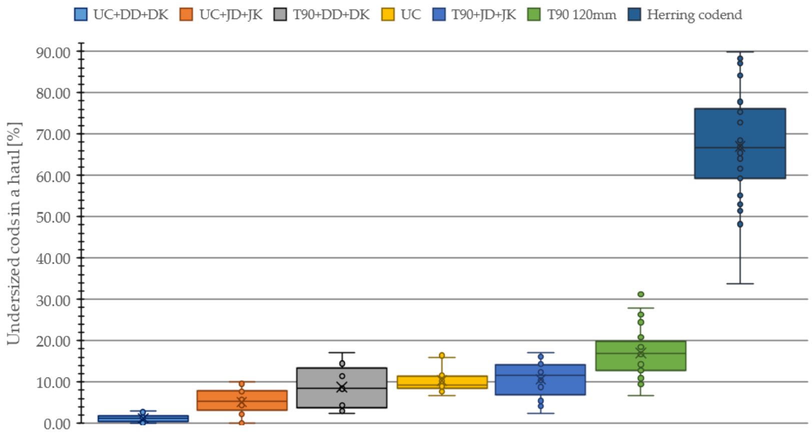


Figure 18. A box and whisker plot of percentage of undersized cod (<35 cm) in one haul in years 2019–2023.

In order to properly assess the differences in particular codend performances in view of the most important issue of the study—the selectivity—a *t*-test (for comparing means) with unequal variances (due to different SDs in codend populations) was conducted. This is a widely accepted technique in early statistical investigations. Details of the *t*-test results are presented in Table 3 (comparison against main benchmark UC + DD + DK) and 4 (comparison against UC + JD + JK as the second codend in the selectivity assessment).

Table 3. Statistical comparison of % catch of undersized cod using UC + DD + DK codend vs. other codends.

	UC + DD + DK	UC + JD + JK	UC	T90 + DD + DK	T90 + JD + JK	T90	Herring
Mean [%]	**1.231**	5.119	10.361	8.729	10.666	17.011	67.036
Variance [%]	**0.878**	8.661	8.619	28.290	18.366	38.443	158.913
SD [%]	**0.937**	2.943	2.936	5.319	4.286	6.200	12.606
Observations no.	**38**	34	20	9	20	22	35
Deg. of freedom	-	39	21	8	20	22	34
t-stat	-	−7.377	−13.550	−4.214	−9.724	−11.860	−30.804
$P(T \leq t)$ one-tail	-	3.27×10^{-9}	3.76×10^{-12}	1.47×10^{-3}	2.53×10^{-9}	2.49×10^{-11}	1.00×10^{-26}

It can be concluded that UC + DD + DK significantly outperforms (from a statistical point of view) other types of codend in terms of selectivity, including the simpler innovative construction of UC + JD + JK. Namely, assuming a significance level of alpha = 0.05, one can reject in all cases the null hypothesis, thus confirming that the selectivity means are quite different, and additionally the mean for UC + DD + DK is much lower than for other codend variants, which is also presented in Figures 16 and 18. Probability data provided in the last row of Table 3 (P(T ≤ t) one-tail), notably very low in observations, mean that for a practical significance level of alpha = 0.05, one has P(T ≤ t) < alpha and a t-statistic lying within the one-sided critical region of the t-statistic distribution, thus enabling one to reject the null hypothesis.

It can be concluded that UC + JD + JK also significantly outperforms other types of codend in terms of selectivity, though probability data provided in the last row of the Table 4 mean that rejection of null hypothesis is weakest for T90 + DD + DK. This justifies the research assumption that addition of innovative devices slowing the water flow to that of a standard T90 codend will also significantly reduce the number of undersized fish in a catch, although not as much as when using them with the more selective UC codend. Further research on this issue is necessary as the number of hauls with T90 + DD + DK was the lowest due to technical failure of the codend sustained in 2019.

Table 4. A *t*-test of % catch of undersized cod using UC + JD + JK codend vs. other codends.

	UC + JD + JK	UC	T90 + DD + DK	T90 + JD + JK	T90	Herring
Deg. of freedom	-	40	9	30	27	38
t-stat	-	−6.330	−1.958	−5.121	−8.405	−28.275
P(T ≤ t) one-tail	-	8.11×10^{-8}	0.041	8.27×10^{-6}	2.57×10^{-9}	1.98×10^{-27}

Table 5 and Figure 19 present differences between the percentage of undersized cod caught with the most selective UC + DD + DK codend and the non-selective herring codend using double bottom trawls in 2023.

Table 5. Percentages of undersized cod caught with UC + DD + DK codend and non-selective herring codend by double bottom trawling in 2023.

Haul No.	UC + DD + DK [%]	Herring Codend [%]	Difference [% Points]
1	3.03	59.19	56.16
2	4.92	65.43	60.51
3	0	68.52	68.52
4	0	61.60	61.60
5	4.20	67.93	63.73
6	4.84	65.20	60.36
7	4.65	84.26	79.61
8	4.13	55.43	51.30
9	4.43	55.20	50.77
10	3.72	67.75	64.03
	Mean		**61.66**
	SD		**8.42**
	Pearson's coefficient of UC + DD + DK % and herring %		**0.09**
	Spearman's coefficient of UC + DD + DK % and herring %		**0.05**

The mean difference between the percentage of undersized cod caught by the UC + DD + DK codend and non-selective herring codend using double bottom trawls in 2023 was 61.7% points with an SD of 8.4% points. The distribution of the frequency of measured differences allocated into 5% point classes (see Figure 19) has not been validated due to the low sample number (the number of comparative hauls by double bottom trawling was 10), but one can assume that there is no or negligible correlation between percentages of undersized cod with the UC + DD + DK codend and the non-selective herring codend as correlation coefficients of Pearson and Spearman are, respectively, 0.09 and 0.05 (a relationship such as a higher percentage for the non-selective codend and a higher percentage for the selective one does not exist—the variables do not tend to change together at either a constant or a non-constant rate).

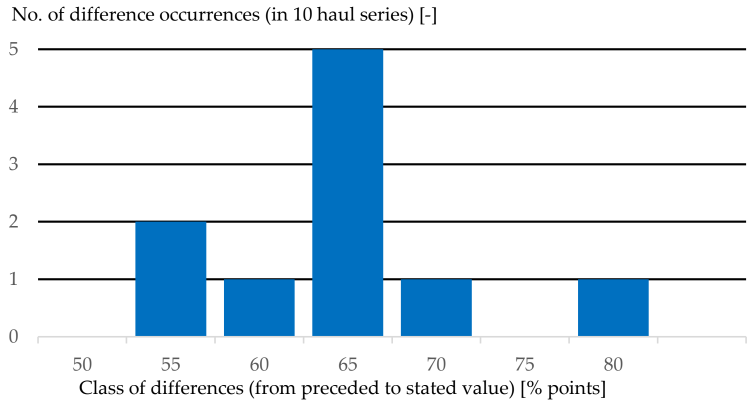
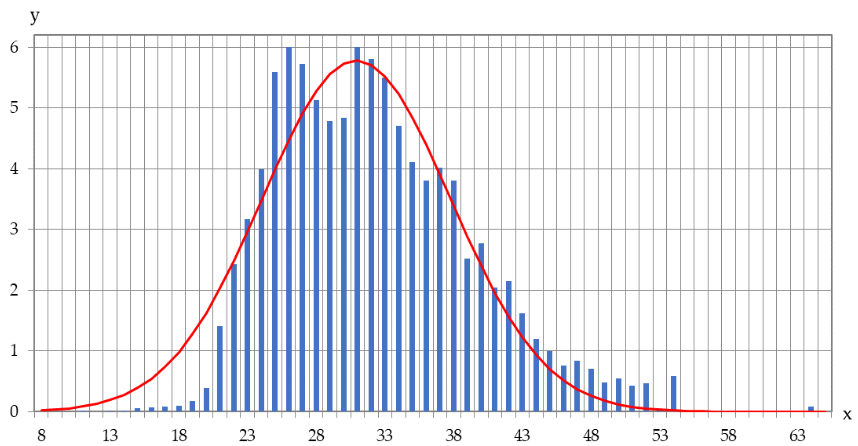
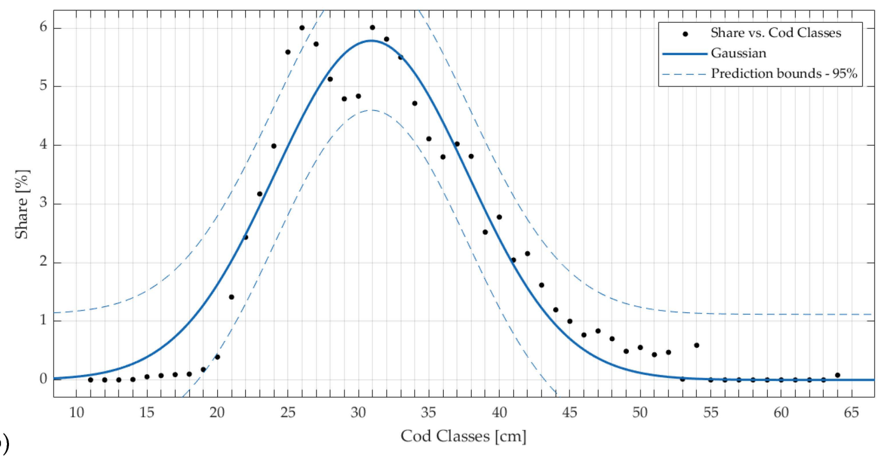


Figure 19. Number of occurrences for differences between percentages of undersized cod caught with UC + DD + DK codend and non-selective herring codend by double bottom trawling in 2023 allocated into classes.

Figure 20a,b additionally shows the results of Baltic cod length measurements made in 2023 from hauls with a herring codend without any selectivity (10,587 individuals measured). The x-axis represents 57 classes of cod length (from 8 to 65 cm long, clustered every 1 cm); the y-axis represents the class share [%] in the caught cod mass.



(**a**)



(**b**)

Figure 20. The length structure of cod caught in 2023: (**a**) clustered column chart: *x*-length classes, *y*—percentage of cod lengths in the total cod mass of catches by herring codend (share) with fitted probability density function (in red); (**b**) Gaussian PDF with 95% prediction bounds of cod class share.

The distribution of caught cod classes fits well a Gaussian model equivalent to a normal PDF given by Equation (1):

$$y = ae^{-\frac{1}{2}\left(\frac{x-b}{c}\right)^2} = \frac{1}{c\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{x-b}{c}\right)^2} \quad (1)$$

where y is the class share [%] in catch mass, x is the length class [cm], a = 5.8% is the amplitude of the share, b = 30.9 cm is the centroid of the class (mean cod length), and c = 6.9 cm is the standard deviation (SD) of classes related to their share. The R^2 coefficient of this fit goodness is 0.93 (the square of the correlation between the measured values and the modelled values). According to the percentage of classes and fitted PDF, approximately 68% of the caught sample of cod were in sizes from 24 cm to 38 cm (mean ± SD), 66% were in classes below 35 cm, and 34% were in classes equal to 35 cm and over. It should be noted, however, that there is a distinct drop in distribution of cod sizes in the range of 27 to 30 cm.

4. Discussion and Conclusions

The conducted research trawls clearly indicate that the use of an innovative ultracross codend of 120 mm mesh with devices reducing the water flow speed (tarpaulin diffusers and 120 mm net confusors) significantly reduces the number of undersized cod (<35 cm) in a catch comparing to other codend solutions. Assuming a significance level of alpha = 0.05, one can reject in all cases the null hypothesis, thus confirming that the selectivity means are quite different, and additionally that the mean for UC + DD + DK is much lower than for other codend variants. The standard European T90 codend, without innovative devices reducing the water flow speed, retained, on average, 17% of undersized cod, while the UC + DD + DK innovative codend retained only 1.2% of undersized cod, which is 14 times less, and the UC with one tarpaulin diffuser and one 120 mm net confusor (UC + JD + JK) retained 5.1% of undersized cod, which is 3.3 times less. Comparison of the high selectivity achieved by UC + DD + DK for cod of length < 35 cm with the length structure of cod in the testbed area (Figure 20) leads to the conclusion that this codend enables the precise selection of fish quite close to the 35 cm limit (68% of cod caught non-selectively were of sizes from 24 cm to 38 cm, but only 1.2% of cod caught selectively were less than 35 cm). This selectivity is steady as no correlation between the percentages of undersized cod caught by UC + DD + DK and the non-selective herring codend while using a double bottom trawl set in 2023 was found and statistically confirmed.

The obtained results are also very promising in terms of invisible discards and the subsequent mortality of escaped fish. At slower water speeds inside the trawl set, the fish which escaped during hauling had a greater chance of survival. Construction of a special divided small-mesh cover for the codend allowed for the determination of the amount as well as the length and mass of cod escaping from the codend while hauling the trawl gear. The average percentage of cod which managed to escape from the innovative codends was 36% ± 5.4%(SD). At the same time, it should be borne in mind that one of the factors that determined the number of undersized cod during the trawl fishing research was the length structure of the Baltic cod population (as presented in Figure 20). Other factors such as (1) seasonality (especially spawning season), (2) fishery area, and (3) skipper competency/experience have not been studied during the present research.

The most serious threat to cod fishery in the Baltic Sea is the decline in cod stock. In the current situation for fishermen, carrying out further research of innovative codends may provide reliable data that can be used to determine the economic profitability of fishing and precisely determine the size of Baltic cod resources. This will allow the fishing community to gain significant arguments in discussions regarding catch limits, fishing bans, fishing tools, and methods, which may in fact translate into the future of cod fishing in the Baltic Sea and the fate of fishing vessel owners, fishermen, and their families.

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K.B., G.K. and A.Ż.; data curation, K.B., G.K. and A.Ż.; writing—original draft preparation, P.Z.; writing—review and editing, P.N., K.B., J.A. and A.Ż.; visualisation, P.Z., K.B. and J.A.; supervision, P.Z.; project administration, M.K.; funding acquisition, P.Z., P.N. and M.K. All authors have read and agreed to the published version of the manuscript.

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