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One mesh does not fit all: A dual compartment codend provides flexible selectivity opportunities to manage mixed fisheries

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ABSTRACT

Fisheries management is moving from a single-species to an ecosystem-based approach to better balance the technical, biological, and economic aspects of the many mixed-species fisheries in the world. Most mixed fisheries are conducted with trawl gears, which have a hereditary challenge of providing a species and size selectivity that meets the development in management objectives of reducing unwanted catch. When fishing on sympatric species, a codend that allows separation of species into different compartments during towing can provide separated catch fractions with contrasting selectivity opportunities. In a case study, we quantified the processes of vertical separation and length-based selectivity for a dual compartment codend having an upper, large mesh compartment intended for cod (*Gadus morhua*) and a lower, small mesh compartment intended for *Nephrops* (*Nephrops norvegicus*). This allowed identification of which processes to improve to reduce unwanted catch. The gear concept delivered a complex selectivity profile while enabling high flexibility to adjust selectivity, also at sea, and provides a tool for the industry to ensure better compliance with increasing management ambitions. An unusual selectivity curve for cod resulted from the contrast in mesh size between the two compartments. Cod and *Nephrops* smaller than and just above the minimum conservation reference size (MCRS) were efficiently released through the 120 mm square meshes in the upper and the 60 mm square meshes in the lower compartment, respectively. Cod (47%) had a low probability of escaping when caught in the lower compartment, and *Nephrops* (9%) were lost when caught in the upper compartment. A compartment in the dual compartment codend may easily be changed at sea to adjust the selectivity according to the mix of species encountered, available quota portfolio, and management regime.

1. Introduction

The regions of the world intensively managing the fishing mortality have healthier fish stocks than regions with little fisheries management (Hilborn et al., 2020). A common management approach used by management bodies like the International Council for the Exploration of the Sea (ICES), General Fisheries Commission for the Mediterranean (GFCM), and US National Marine Fisheries Service (NOAA Fisheries), is to make catch advice for single species from stock assessments based on the Maximum Sustainable Yield principle (Sun et al., 2023). In the European Union, annual total allowable catches (TACs) are set individually for most fish stocks based on the advice given by ICES. The TACs are then shared among the European countries as national quotas, which are distributed among fishing vessels (https://ec.europa.eu/oceans-and-fisheries/fisheries/rules/fishing-quotas_en), e.g., according to their catches the previous year.

Most of the global fisheries harvest a mix of species, and the same species are fished with several fishing gears (Dolder et al., 2018; Sun et al., 2023). When regulating these mixed fisheries using a single-species management approach, technical, biological, and economic outputs are not considered, such as fisher/fleet strategies or fishing gear types used, species interactions, and economic viability with changing catch composition, respectively (Gourguet et al., 2013; Sun et al., 2023). To meet these challenges, there has been a paradigm shift to an ecosystem-based management (e.g., NOAA, 2018; ICES, 2020a), which includes trade-offs associated with balancing ecological, economic, and social objectives (Gourguet et al., 2013). Methods for how this new, holistic management regime can be supported are being

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explored, e.g., bio-economic and viability modelling (Péreau et al., 2012; Gourguet et al., 2013), fishing mortality ranges and multi-stock harvest control rule (Rindorf et al., 2017; Ulrich et al., 2017; Garcia et al., 2020), and dynamic ocean management (Townsend et al., 2019).

In the European Union, the transition to ecosystem-based management is through the implementation of the European Common Fisheries Policy. This includes transforming the quota portfolio of the fisher from landing quotas to catch quotas and, like other managed regions, introducing remote electronic monitoring onboard the fishing vessels (REM, van Helmond et al., 2020). Small individuals that previously was discarded must be landed and deducted from the quotas to comply with the regulation (EU, 2013, Article 15; §1). The landing obligation and REM thereby directly couples catchability and selectivity to economy and make every fish count. In this way, the fishers are given an incentive to minimize or eliminate unwanted species and sizes to maximize the capitalization of the quota portfolio. Fishers may seek optimal catch composition by carefully choosing when, where, and how to fish (Branch and Hilborn, 2008). Individual Transferable Quotas (ITQs), i.e., vessel quotas that can be bought, sold, and leased to other vessels, allow fishers to better match their quota portfolio to the expected or experienced catch composition presupposed that the needed quotas are available and affordable (Péreau et al., 2012). The success of the fisher to balance the catch composition and quota portfolio depends on the distribution of the different species and sizes relative to each other, but many species are sympatric and therefore not easily separated spatiotemporally (Dolder et al., 2018). This balance is therefore challenged when some species are subjected to low TACs and may, when their quotas are exhausted, choke fisheries for other species for which the TAC is higher (Sun et al., 2023). Similarly, a large catch of individuals below the minimum conservation reference size (MCRS) will devaluate the quota as they cannot be sold for human consumption (EU, 2013, Article 15; §11).

If unwanted species and sizes cannot be avoided geographically, a reduction of their mortality can be managed by changing the catchability and selectivity of the fishing gear. Gear restrictions is a common management tool and in the global mixed fisheries, trawls are the most widely used gears (Sun et al., 2023). While selective fishing gears contribute to reducing the amounts of discards in the word (Gilman et al., 2020), the lack of suitable selectivity for each of the multiple species caught in trawls continue to create large unwanted catches and challenge the management of technical measures involving gear specifications. Changing the design of trawl gears to increase the selectivity of unwanted species and sizes sometimes result in a concurrent loss of target species (Catchpole and Revill, 2008), e.g., when small meshes are required to retain the smaller sized target species (Seidel, 1975; Catchpole et al., 2006; Krag et al., 2008; Frandsen et al., 2009; Santos et al., 2018), or when the morphology of target and unwanted species are similar (Sistiaga et al., 2011). Trawls divided into different compartments can separate species during towing based on differences in vertical distribution, and subsequently provide separated catch fractions with different selectivity opportunities, e.g., by using netting with meshes of different size or geometry or even keeping one codend compartment open (Melli et al., 2020). This gives the opportunity to flexibly modify gear selectivity to changes in the encountered catch composition while at sea. In addition, a gear in which catch is separated into different compartments may have prospects of improving quota values through positive effects on for example fish quality (Karlsen et al., 2015) and discard survival (Savina et al., 2019).

Separation of catch has been widely tested in the *Nephrops* fishery (*Nephrops norvegicus*, Santos et al., 2018; Melli et al., 2018, 2019; Cosgrove et al., 2019; Karlsen et al., 2019), to some extent in the demersal whitefish fishery (Pacific cod, *Gadus macrocephalus*, Stone and Bubliz, 1995; haddock, *Melanogrammus aeglefinus*, Valdemarsen et al., 1985; Smith et al., 2018), and to a lesser degree in the shrimp (Seidel, 1975) and industrial trawl (Bailey et al., 1983) fisheries. Most commonly, one (Main and Sangster, 1985; Smith et al., 2018) or two (Main and Sangster, 1982; Bailey et al., 1983) horizontal separator panels have been used in either the whole gear (Main and Sangster, 1982; Galbraith and Main, 1989), with some distance to the groundgear (Stone and Bubliz, 1995; Ferro et al., 2007; Holst et al., 2009; O'Neill and Summerbell, 2019), or in the extension leading to a split codend that collects the catch from each compartment separately (Graham and Fryer, 2006; Krag et al., 2009a, 2009b; Karlsen et al., 2019).

This multi-selective design concept is demonstrated using the *Nephrops* fishery in the North Sea and sound of Skagerrak between Denmark and Norway as a case study. Apart from the target species, *Nephrops*, several fish species are also caught in this demersal trawl fishery. The most common bycatch species are Atlantic cod (*Gadus morhua*), haddock, whiting (*Merlangius merlangus*), saithe (*Pollachius virens*), European hake (*Merluccius merluccius*), monkfish (*Lophius piscatorius*), witch flounder (*Glyptocephalus cynoglossus*), European plaice (*Pleuronectes platessa*), and lemon sole (*Microstomus kitt*). Depending on the status of the fisher's quota portfolio and the market at the time of the fishery, these species may be unwanted or of commercial interest. For simplicity, the demonstration of the multi-selective design concept in this study will be restricted to *Nephrops* and cod. The current poor status of many cod stocks being exploited in northern Europe (e.g., ICES, 2020b-e) has led to avoidance measures (e.g., selective measures, spawning closures) and limited TACs for unavoidable cod bycatch in fisheries targeting other species (EU, 2021a, b, c). Cod is widely distributed in the North Sea, Skagerrak, and Kattegat (ICES FishMap, 2006; ICES, 2019a) and is taken as a bycatch species in most gears used in demersal and pelagic fisheries throughout the year, implying that the fishing mortality of these stocks are linked to the effort directed to these fisheries (ICES FishMap, 2006; ICES, 2019b). Consequently, it is desirable to find solutions to substantially reduce cod catches in trawl fisheries.

The aim of this study was to quantify the overall selective efficiency of a dual compartment codend, a design principle that has global applicability, tested in the *Nephrops* fishery. Furthermore, the three processes leading to the overall selective efficiency was quantified separately; (*i*) the vertical separation of the caught species that is a prerequisite for a subsequent differential size selectivity; (*ii*) one in the upper compartment suitable for cod, and (*iii*) another in the lower compartment suitable for *Nephrops*. This enables identification of which process to improve to reduce unwanted catch or loss of target species in a system where compartments easily can be changed at sea to optimize selectivity according to the current catch composition, quota rights and concerns for species like cod that potentially can develop into choke species. A series of catch indicators were estimated to assist the evaluation of the reduction in cod catches and retention of *Nephrops* catches in relation to the minimum conservation reference sizes (MCRS) in Skagerrak/Kattegat and North Sea areas, also in a scenario where the fisher is targeting only one of the two species.

2. Materials and methods

2.1. Gear design

The selective dual compartment codend (test codend) were made of Ultra Cross® knotless netting (4 mm twine thickness) with 120 mm square mesh in the upper compartment, and 60 mm square mesh in the lower compartment (Fig. 1a). These mesh sizes were chosen to retain only large, better priced sizes of cod (MCRS: 30 cm for cod in Skagerrak

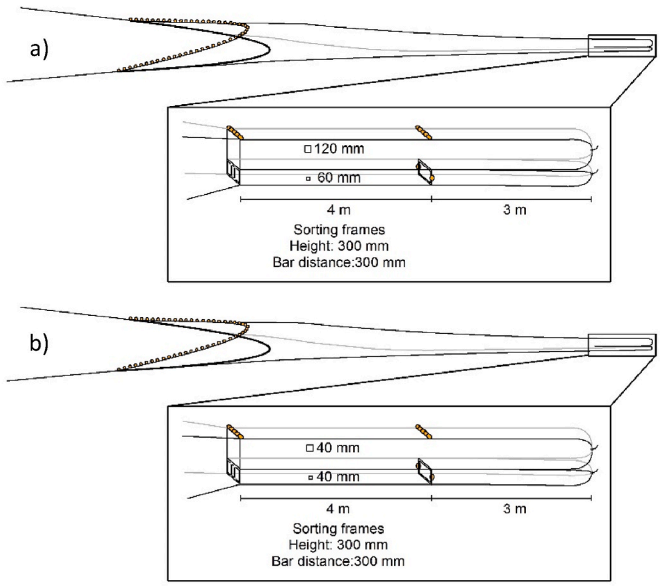

Fig. 1. The two dual compartment codend design used in a twin set-up during the sea trial. a) The test codend with 120 mm and 60 mm square meshed in the upper and lower compartment, respectively. b) The control codend with 40 mm diamond meshes in a T45 configuration to obtain a square mesh geometry in both compartments. A total of ten floats (1L) were used for each codend to ensure opening in the section and to compensate for the weight of the steel frames.

and Kattegat, and 35 cm in the North Sea) and other round fish in the upper compartment, as well as avoid catches of *Nephrops* smaller than the MCRS while retaining those larger than MCRS in the lower compartment. The limit for undersized *Nephrops* in Skagerrak and Kattegat areas changed from 40 mm carapace length (CL) to 32 mm CL in 2016, while it is 25 mm CL in the North Sea. In the control codend, the knotted netting of both compartments was made of 40 mm diamond mesh of a single 1.8 mm braided polyethylene twine turned 45° (T45) to obtain a square mesh geometry (Fig. 1b). This small mesh size was not intended for the commercial fishery. The control codend was mounted to the tapered section as square meshes to obtain open compartments, stable mesh geometry, and maximal water flow through the small meshes. In the forward 2 m of both codends, the two compartments were fixed together by a 40 mm T45 diamond mesh horizontal separator panel to prevent twisting, while the aft end were split to give separate collecting bags for the two compartments. All mesh sizes were measured using an OMEGA mesh gauge (Fonteyne, 2005). The entrances of the upper compartments were about 60 cm high and comprised two-thirds of the total height of the gear (Fig. 1). The height of the lower compartments was fixed to 30 cm by a frame made from 20 mm stainless steel pipes mounted at its entrance and comprised the remaining one-third of the total height. The frame had two vertical guide bars placed 30 cm apart to encourage fish to swim into the upper compartment (Krag et al., 2009b). A similar frame without the vertical bars was mounted 4 m aft of the compartment entrance to aid full opening in the lower compartment (Karlsen et al., 2019). To further optimize catch separation, the foremost frame was placed in the transition between the tapered and non-tapered section of the gear where *Nephrops* were expected to be the close to the lower panel (Fig. 1). Five 1 L floats were attached across the top panel above both frames to ensure good opening in the upper compartment and to compensate for the weight of the frames.

2.2. Sea trial

The experiment was conducted aboard a commercial trawler (162 gross register tons, 22 m, 299 kW) with a three-wire towing rig (i.e., a twin rig configuration) allowing the test and control codends to be fished simultaneously. The two codends were attached to the commercial trawls that the vessel normally use in the *Nephrops* fishery. The trawls had a 47.5 m floatline and the groundgear measured 54.5 m. The circumference comprised 500 meshes (80 mm diamond) and gave a headline height of ca. 2 m. Fishing was conducted during day and night hours from September 23 to October 1, 2013 following commercial practice on commercial fishing grounds in Skagerrak. The overall geometry of the towing rig was recorded every 15 min using double spread sensors (Marport). The geometry of the entrance of the upper compartment was monitored during the first, shallower haul using a camera (GoPro Hero 3+) attached to the top panel about 1.5 m in front of the entrance of the upper compartment facing towards the entrance of the test codend. The haul duration was in general set to a shorter duration than the commercial practice to avoid the risk of large catches reaching the separation point of the small mesh control codend, thereby risking mixing the catches of the two compartments. The catches from all four compartments were kept separate during handling and measuring. The total length of cod was measured by rounding down to the nearest centimetre, and the carapace length of *Nephrops* to the nearest millimetre. In the subsequent analysis, 0.5 cm was added for cod and 0.5 mm for *Nephrops* (Krag et al., 2014). All individuals from each species were measured in each haul.

2.3. Modelling and analysis of size selectivity in the test codend

The experimental design (Fig. 1) consisted of a test and control gear, each with a dual compartment codend, which were fished in parallel so that the catch in terms of number n_l of individual cod or *Nephrops* belonging to size class l for each haul was shared in four fractions; $nT1_l$ (number in upper compartment of test codend), $nT2_l$ (number in lower compartment of test codend), $nC1_l$ (number in upper compartment of control codend) and $nC2_l$ (number in lower compartment of control codend). The purpose of the analysis was to estimate the combined (overall) size selectivity $r_{combined}(l)$ in the test codend (T1 + T2) as well as the size selectivity in its individual compartments (T1 and T2) for cod and *Nephrops* entering the specific compartment ($r1(l)$ and $r2(l)$). The modelling and estimation of the size selectivity was carried out separately for cod and *Nephrops*. Only hauls containing at least 10 individuals of the given species in each compartment were included in the analysis (Krag et al., 2014). We were interested in estimating the average size selectivity for each size class. The analysis was therefore conducted summed over hauls (Herrmann et al., 2012). For modelling how the catch was shared among the four fractions $nT1_l$, $nT2_l$, $nC1_l$ and $nC2_l$, we introduced five assumptions. i) The probability for a cod or *Nephrops* to enter the test codend conditioned entering one of the two codends can summed over hauls be modelled by a length independent split parameter SP as usually assumed for paired gear size selectivity modelling (Santos et al., 2016). ii) The length dependent probability $rc(l)$ for a cod or *Nephrops* to enter the upper compartment in the codend conditioned it enters one of the two compartments is similar in test and control codends when summed over hauls. $rc(l)$ is modelled using a polynomial logistic regression following the approach for studying vertical separation of fish and *Nephrops* in trawls described by Karlsen et al. (2019) with parameters (p_0,p_1,p_2,p_3,p_4):

$$rc(l,\boldsymbol{\gamma_c}) = \frac{exp(f(l,\boldsymbol{\gamma_c}))}{1.0 + exp(f(l,\boldsymbol{\gamma_c}))}$$

with (1)

$$f(l,\boldsymbol{\gamma_c}) = \sum_{i=0}^{4} p_i \times \left(\frac{l}{100}\right)^i = p_0 + p_i \times \frac{l}{100} + p_2 \times \frac{l^2}{100^2} + \ldots + p_4 \times \frac{l^4}{100^4}$$

The scaling of parameters for length in equation (1) is applied to scale the parameters to ease the estimation, meaning avoiding over/underflow for higher order terms. iii) The size selection *r1(l)* in the upper compartment of the test codend can be described by a logit size selection model (Wileman et al., 1996) with parameters $L50_1$ and SR_1:

$$r1(\boldsymbol{\gamma_1},l) = \frac{exp\left(\frac{ln(9)}{SR_1} \times (l - L50_1)\right)}{1.0 + exp\left(\frac{ln(9)}{SR_1} \times (l - L50_1)\right)} \quad (2)$$

iv) The size selection r2 in the lower compartment of the test codend can be described by a logit size selection model with parameters $L50_2$, SR_2:

$$r2(\boldsymbol{\gamma_2},l) = \frac{exp\left(\frac{ln(9)}{SR_2} \times (l - L50_2)\right)}{1.0 + exp\left(\frac{ln(9)}{SR_2} \times (l - L50_2)\right)} \quad (3)$$

v) Both compartments in the control codend can be considered non-selective regarding cod and *Nephrops* if there is no overlap with the size selection in the test codend.

Assumption i)-v) leads to that the length dependent catch sharing between the four compartments (Fig. 1) can be modelled and described based on the species dependent values for the 10 parameters (P_0, P_1, P_2, P_3, P_4, $L50_1$, SR_1, $L50_2$, SR_2, SP).

Let n_l be the number of cod or *Nephrops* of length l that enters in front of one of the two separator frames in one of the two gears (test or control). Then based on the assumed model i)-v) the expected number of cod or *Nephrops* of length l caught in each of the four compartments will be:

$$\begin{aligned} nT1_l &= SP \times rc(\boldsymbol{\gamma_c},l) \times r1(\boldsymbol{\gamma_1},l) \times n_l \\ nT2_l &= SP \times (1.0 - rc(\boldsymbol{\gamma_c},l) \times r2(\gamma_2,l) \times n_l \\ nC1_l &= (1.0 - SP) \times rc(\boldsymbol{\gamma_c},l) \times n_l \\ nC2_l &= (1.0 - SP) \times (1.0 - rc(\boldsymbol{\gamma_c},l)) \times n_l \end{aligned} \quad (4)$$

Where we have introduced the following parameter vectors to make the description shorter:

$$\boldsymbol{\gamma_c} = \begin{pmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \\ p_4 \end{pmatrix} \quad \boldsymbol{\gamma_1} = \begin{pmatrix} L50_1 \\ SR_1 \end{pmatrix} \quad \boldsymbol{\gamma_2} = \begin{pmatrix} L50_2 \\ SR_2 \end{pmatrix} \quad \boldsymbol{\gamma} = \begin{pmatrix} \boldsymbol{\gamma_c} \\ \boldsymbol{\gamma_1} \\ \boldsymbol{\gamma_2} \\ SP \end{pmatrix} \quad (5)$$

Based on equation (4) the total number caught will be:

$$nR_1 = nT1_l + nT2_l + nC1_l + nC2_l \quad (6)$$

Which based on (4)-(5) can be written as:

$$nR_l = (1.0 - SP \times (1.0 + rc(\boldsymbol{\gamma_c},l) \times (r2(\boldsymbol{\gamma_2},l) - r1(\boldsymbol{\gamma_1},l)) - r2(\boldsymbol{\gamma_2},l))) \times n_l \quad (7)$$

The observed length dependent catch shares in the four compartments can, based on (4) and (7), be written as:

$$\begin{aligned} RT1(\gamma,l) &= \frac{nT1_l}{nR_l} = \frac{SP \times rc(\boldsymbol{\gamma_c},l) \times r1(\boldsymbol{\gamma_1},l)}{(1.0 - SP \times (1.0 + rc(\boldsymbol{\gamma_c},l) \times (r2(\boldsymbol{\gamma_2},l) - r1(\boldsymbol{\gamma_1},l)) - r2(\boldsymbol{\gamma_2},l)))} \\ RT2(\gamma,l) &= \frac{nT2_l}{nR_l} = \frac{SP \times (1.0 - rc(\boldsymbol{\gamma_c},l)) \times r2(\boldsymbol{\gamma_2},l)}{(1.0 - SP \times (1.0 + rc(\boldsymbol{\gamma_c},l) \times (r2(\boldsymbol{\gamma_2},l) - r1(\boldsymbol{\gamma_1},l)) - r2(\boldsymbol{\gamma_2},l)))} \\ RC1(\gamma,l) &= \frac{nC1_l}{nR_l} = \frac{SP \times rc(\boldsymbol{\gamma_c},l)}{(1.0 - SP \times (1.0 + rc(\boldsymbol{\gamma_c},l) \times (r2(\boldsymbol{\gamma_2},l) - r1(\boldsymbol{\gamma_1},l)) - r2(\boldsymbol{\gamma_2},l)))} \\ RC2(\gamma,l) &= \frac{nC2_l}{nR_l} = \frac{(1.0 - SP) \times rc(\boldsymbol{\gamma_c},l)}{(1.0 - SP \times (1.0 + rc(\boldsymbol{\gamma_c},l) \times (r2(\boldsymbol{\gamma_2},l) - r1(\boldsymbol{\gamma_1},l)) - r2(\boldsymbol{\gamma_2},l)))} \end{aligned} \quad (8)$$

Fishing with four compartments simultaneously in which a cod or *Nephrops* can be caught, there is a mutual dependency between compartments where they length-dependently share the total catch between them. The data is thus multinominal, and we therefore formulated a likelihood function assuming that the data for individual length classes will follow a four-compartment multinominal distribution. Therefore, to obtain the values for the parameters $\boldsymbol{\gamma}$, we minimized the negative log likelihood function for the observed experimental data summed over the hauls included in the analysis:

$$-\sum_i \sum_l \{nT1_{il} \times ln(Rt1(\gamma,l)) + nT2_{il} \times ln(RT2(\gamma,l)) + nC1_{il} \times ln(RC1(\gamma,l)) + nC2_{il} \times ln(RC2(\gamma,l))\} \quad (9)$$

Minimizing (9) with respect to parameters $\boldsymbol{\gamma}$ corresponds to maximizing the likelihood for the observed data. The outer summation in (9) is over hauls *i* and the inner over length classes *l*.

Having identified the values for parameters $\boldsymbol{\gamma}$, we can use them to estimate the combined $r_{combined}$ selectivity in the test codend based on:

$$r_{combined}(\boldsymbol{\gamma_c},\boldsymbol{\gamma_1},\boldsymbol{\gamma_2},l) = rc(\boldsymbol{\gamma_c},l) \times r1(\boldsymbol{\gamma_1},l) + (1.0 - rc(\boldsymbol{\gamma_c},l)) \times r2(\boldsymbol{\gamma_2},l) \quad (10)$$

And we can estimate the selectivity in the two compartments of the test codend by applying equations (2) and (3). In addition, setting $r1(\boldsymbol{\gamma_1},l)$ and $r2(\boldsymbol{\gamma_2},l)$ to 0.0 for all sizes *l* we can with (10) also predict what would be the combined selectivity if we were fishing without an upper or lower compartment of the test codend respectively.

The confidence limits for the parameters $\boldsymbol{\gamma}$ and for the size selection curves $r_{combined}(l)$, *r1(l)* and *r2(l)* were estimated using a double bootstrap method that accounts for the uncertainty resulting from between and with-in haul variation in size selection (Millar, 1993). We performed 1000 bootstrap repetitions to calculate the 95% percentile confidence limits (Efron, 1982; Chernick, 2007) for the selection parameters and curves. The model's ability to describe the experimental data was evaluated based on the fit statistics p-value, model deviance versus degrees of freedom (DOF), as well as inspection of how the model curve reflects the length-based trend in the data (Wileman et al., 1996). The p-value expresses the likelihood of obtaining at least as big a discrepancy between the fitted model and the observed experimental data by coincidence. In case of poor fit statistics (i.e., p-value being < 0.05; deviance being $>>$ DOF), the model curve plots were inspected to determine whether the poor result was due to structural problems when describing

Table 1
Operational conditions.

Haul	Day (D) or night (N)	Towing time (hh:mm)	Wind speed (m/s)	Wave height (m)	Towing speed (knots)	Fishing depth (m)	Trawl door distance (m)	Wire length (m)
1	N	2:50	5	0–1.0	2.5	56	83	235
3	D	2:23	8	0–1.0	2.6	113	100	377
5	N	2:15	3	0–0.5	2.6	132	95	471
7	D	2:30	4	0–0.5	2.6	141	100	424
8	N	3:30	5	0–1.0	2.6	122	100	424
10	D	1:15	3	0–0.5	2.6	132	100	424
11	N	3:15	2	0	2.7	132	100	424
13	D	2:23	4	0–0.5	2.7	141	100	471
14	N	2:45	4	0–0.5	2.6	141	100	471
16	D	3:00	4	0–0.5	2.7	141	100	471
17	N	2:45	5	0–0.5	2.6	141	97	424
20	D	2:35	5	0–0.5	2.7	141	100	471
21	N	2:30	8	0–0.5	2.6	169	90	518
24	N	2:40	8	0–0.5	2.6	160	100	471

the experimental data using the model or if it was due to over-dispersion in the data (Wileman et al., 1996). The analysis was carried out using the software SELNET (Herrmann et al., 2012), which implements the models and the bootstrap method described above.

2.4. Estimation of catch indicators to evaluate test codend performance

Three catch indicators were estimated to identify any challenges when fishing with a specific codend on the population structure of a species where the fishing is conducted, when considering given catch goals of the fisher in the *Nephrops* fishery. All three indicators were estimated individually for cod and *Nephrops* and for both Skagerrak/Kattegat and North Sea as the MCRS for the two areas are defined differently. The first indicator was used to evaluate the overall degree of retention of individuals < MCRS and loss of individuals ≥ MCRS in the test codend (Wienbeck et al., 2014):

$$
\begin{aligned}
nP &= 100 \times \frac{\sum_i \sum_l \{nT1_{il} + nT2_{il}\}}{\sum_i \sum_l \{nC1_{il} + nC2_{il}\}} \\
nP- &= 100 \times \frac{\sum_i \sum_{l<MCRS} \{nT1_{il} + nT2_{il}\}}{\sum_i \sum_{l<MCRS} \{nC1_{il} + nC2_{il}\}} \\
nP+ &= 100 \times \frac{\sum_i \sum_{l>MCRS} \{nT1_{il} + nT2_{il}\}}{\sum_i \sum_{l>MCRS} \{nC1_{il} + nC2_{il}\}} \\
dnRatio &= 100 \times \frac{\sum_i \sum_{l<MCRS} \{nT1_{il} + nT2_{il}\}}{\sum_i \sum_l \{nT1_{il} + nT2_{il}\}}
\end{aligned}
\tag{11}
$$

nP estimates the retention efficiency summed over all sizes for the test codend while considering the size structure of the population caught during the sea trial given by the catch in the control codend. *nP*−and *nP* + estimate the retention efficiency of the population below and above the MCRS, respectively. *nP*− should preferably be low (close to 0), i.e., no or few individuals below MCRS. On the other hand, *nP* + should be high (close to 100), i.e., all, or almost all individuals over MCRS that enter the codend should be retained for species that are targeted according to the catch goal of the fisher. *dnRatio* calculates the species-specific ratio of undersized catch (also called discard ratio) in numbers of individuals assuming a knife-edge split at MCRS, i.e., every fish or *Nephrops* below and above MCRS is released or retained, respectively. The lower the *dnRatio*, the lower the catch of individuals below MCRS and the more suitable the codend is for the specific fishery when the fisher is targeting the species.

The second indicator was used to evaluate the situation when a species is not targeted by the fisher, the retention efficiency if fishing without the upper or lower compartment so all sizes of the species that enter that compartment escape by adjusting Equation (11) to only include T1 or T2, respectively, in the numerator:

$$
\begin{aligned}
nPT1 &= 100 \times \frac{\sum_i \sum_l \{nT1_{il}\}}{\sum_i \sum_l \{nC1_{il} + nC2_{il}\}} \\
nPT1- &= 100 \times \frac{\sum_i \sum_{l<MCRS} \{nT1_{il}\}}{\sum_i \sum_{l<MCRS} \{nC1_{il} + nC2_{il}\}} \\
nPT1+ &= 100 \times \frac{\sum_i \sum_{l>MCRS} \{nT1_{il}\}}{\sum_i \sum_{l>MCRS} \{nC1_{il} + nC2_{il}\}} \\
dnRatioPT1 &= 100 \times \frac{\sum_i \sum_{l<MCRS} \{nT1_{il}\}}{\sum_i \sum_l \{nT1_{il}\}} \\
nPT2 &= 100 \times \frac{\sum_i \sum_l \{nT2_{il}\}}{\sum_i \sum_l \{nC1_{il} + nC2_{il}\}} \\
nPT2- &= 100 \times \frac{\sum_i \sum_{l<MCRS} \{nT2_{il}\}}{\sum_i \sum_{l<MCRS} \{nC1_{il} + nC2_{il}\}} \\
nPT2+ &= 100 \times \frac{\sum_i \sum_{l>MCRS} \{nT2_{il}\}}{\sum_i \sum_{l>MCRS} \{nC1_{il} + nC2_{il}\}} \\
dnRatioPT2 &= 100 \times \frac{\sum_i \sum_{l<MCRS} \{nT2_{il}\}}{\sum_i \sum_l \{nT2_{il}\}}
\end{aligned}
\tag{12}
$$

The third indicator was used to evaluate the degree of retention of individuals < MCRS and loss of individuals ≥ MCRS separately for the upper and lower compartment. The discard ratios are in this case the same as for the second indicator.

$$
\begin{aligned}
nT1 &= 100 \times \frac{\sum_i \sum_l \{nT1_{il}\}}{\sum_i \sum_l \{nC1_{il}\}} \\
nT1- &= 100 \times \frac{\sum_i \sum_{l<MCRS} \{nT1_{il}\}}{\sum_i \sum_{l<MCRS} \{nC1_{il}\}} \\
nT1+ &= 100 \times \frac{\sum_i \sum_{l>MCRS} \{nT1_{il}\}}{\sum_i \sum_{l>MCRS} \{nC1_{il}\}} \\
nT2 &= 100 \times \frac{\sum_i \sum_l \{nT2_{il}\}}{\sum_i \sum_l \{nC2_{il}\}} \\
nT2- &= 100 \times \frac{\sum_i \sum_{l<MCRS} \{nT2_{il}\}}{\sum_i \sum_{l<MCRS} \{nC2_{il}\}} \\
nT2+ &= 100 \times \frac{\sum_i \sum_{l>MCRS} \{nT2_{il}\}}{\sum_i \sum_{l>MCRS} \{nC2_{il}\}}
\end{aligned}
\tag{13}
$$

nT1 estimates the retention efficiency summed over all sizes for the upper compartment of the test codend while considering the size structure of the population caught during the sea trial given by the catch in the upper compartment of the control codend. *nT1*−and *nT1*+ estimate the retention efficiency of the population below and above the MCRS, respectively, in the upper compartment. *nT2*, *nT1*−and *nT2*+ similarly estimates the retention efficiency for the lower compartment. In this case, the *dnRatio* is equal to that of the situation where one codend is open (12). Contrary to the size selection properties, which provide information that is independent of the size structure of the population (i.e., is estimated for each size class), the indicators defined in this section directly depend on the size structure of the fished population (i.e., is estimated for the population, which may vary over space and time; Wienbeck et al., 2014).

To estimate the uncertainty in the indicators (11–13) for cod and *Nephrops*, considering both the effect of between-haul variation and uncertainty related to within-haul variation, we used the same double bootstrapping method as for the size selectivity estimation described above to estimate the 95% confidence limits for the indicator values.

3. Results

3.1. Sea trial

The average (±SD) mesh size (n = 30) of the test gear was 126.10 (±0.92) mm in the upper compartment, and 61.93 (±0.69) mm in the lower compartment, and of the control gear 44.03 (±1.35) mm in the upper compartment and 43.63 (±1.27) mm in the lower compartment. The trial was conducted on commercial fishing grounds under good fishing conditions (Table 1). The duration of the fourteen valid hauls varied between 1.25 h and 3.50 h (mean: 2.63 h). Underwater video recordings showed that the net was open and stable at the entrance of the divided codend during fishing. There were no problems handling the two frames in the lower compartment during the fishing process, and the two vertical bars in the foremost frame did not collect any objects.

In total, 5734 cod and 4205 *Nephrops* were included in the analysis. Five hauls contained less than 20 *Nephrops* in total and were excluded from the analysis for this species (Table 2). Looking at the fit statistics for the model, the *p*-value was above 0.05 for *Nephrops*, but not for cod (Table 3). For cod, the residual deviations between the data and the modelled curve were investigated and no systematic structure was detected. We considered the low p-value to be a consequence of overdispersion in the data and not caused by structural problems in describing the experimental data with the combined model (Wileman et al., 1996).

3.2. Size selectivity

3.2.1. Cod

The model described well the experimental data with small confidence intervals in the size range containing the bulk of the data (Fig. 2). In the control codend, 53% (CI: 50%–56%) of the cod (n = 1954) were caught in the upper compartment (Table 3). The mean size of this proportion of cod was 41 cm (range: 12–96 cm), while it was 35 cm (range: 9 cm–92 cm) for cod caught in the lower compartment. In the test codend, the mean size of the cod caught in the upper compartment was 57 cm (range: 32–98 cm), and 37 cm (range: 7–95 cm) for those caught in the lower compartment.

A comparable number of cod was caught in the lower compartment of the control and test codends as the mesh sizes were similar (Table 3). However, due to the higher selectivity in the upper compartment of the test codend, the proportion of the total catch that were caught in the lower compartment of this codend was higher, i.e., 47% (CI: 44%–50%) and 79% (CI: 75%–84%) in the control and test codend, respectively. There was a length-dependent separation of cod in the test codend. Individuals in the size range 8–44 cm significantly preferred to enter the lower compartment, while larger individuals had a uniform vertical distribution when taking the difference of the compartment heights into consideration (Fig. 3a).

Given that cod was caught in the lower compartment, the probability of being retained by the 60 mm square meshes increased with increasing size for the size range 7–33 cm and gave an L50 (the length at which 50% of the individuals were retained) of 18 cm (Fig. 3b). Smaller and larger individuals in this compartment had the probability of 100% (CI: 0%–100%) escape, or 100% (CI: 68%–100%) retention, respectively. At the MCRS of 30 cm (Skagerrak/Kattegat), the probability of escaping was 2% (CI: 0%–44%), while for cod at MCRS of 35 cm (North Sea) it was 0% (CI: 0%–31%). Given that cod was caught in the upper compartment, the probability of being retained by the 120 mm square meshes increased for the size range 34–66 cm, and the L50 was 50 cm. (Fig. 3c). Smaller and larger individuals in this compartment had the probability of 100 % (CI: 99%–100%) escape, or 100% (CI: 97%–100%) retention, respectively. Thus, at the MCRS of 30 cm (Skagerrak/Kattegat), the probability of escaping was 100% (CI: 100%-100%), while for cod at MCRS of 35 cm (North Sea) it was 99% (CI: 98%–100%).

The combined selectivity for the lower and upper compartments described the overall selectivity performance of the codend (Fig. 3d). Cod smaller than 8 cm and larger than 62 cm were efficiently released or retained, respectively, from the codend irrespective of which compartment they entered. The retention of individuals in between these sizes depended on which compartment they entered. In the size range 8–27 cm, for which the probability of entering the lower compartment was 58%–80%, the retention probability increased with the size of the individuals as their probability of escaping through the 60 mm square meshes decreased. In the size range 28–41 cm, for which the probability of entering the upper compartment increased from 44% to 59%, the retention probability decreased as fish that entered the upper compartment escaped through the 120 mm square meshes. In the size range of 42–62 %, the probability of entering the upper compartment was 60%–68%. The retention increased with size until the fish become too large (≥67 cm of length) to escape through the 120 mm square meshes.

Table 2
Number of individuals in the upper and lower compartment of the control (40 mm/40 mm) and test codend (120 mm/60 mm), respectively. Hauls in bold were not included in the analysis.

Haul	Cod				*Nephrops*			
	Control, lower	Control, upper	Test, lower	Test, upper	Control, lower	Control, upper	Test, lower	Test, upper
1	88	83	64	8	1157	115	905	0
3	248	256	237	58	163	16	154	0
5	63	75	64	21	**6**	**2**	**3**	**0**
7	122	131	101	31	130	12	116	0
8	134	249	190	16	26	13	19	0
10	97	94	70	33	33	2	30	0
11	106	126	135	13	**5**	**2**	**9**	**0**
13	205	232	219	76	156	6	130	0
14	69	125	42	41	**11**	**1**	**4**	**2**
16	235	239	191	49	171	18	174	0
17	88	81	77	21	**1**	**0**	**6**	**0**
20	164	163	127	41	304	37	278	0
21	55	42	53	6	16	5	17	1
24	60	58	51	11	**3**	**0**	**4**	**0**
Total	1734	1954	1621	425	2182	229	1849	3
Analysed	1734	1954	1621	425	2156	224	1823	1

Table 3
Fit statistics.

Species	*p*-value	Deviance	DoF
Cod	0.04	295.06	255
Nephrops	0.95	127.62	155

3.2.2. *Nephrops*

The model described well the experimental data, with small confidence intervals in the size range containing the bulk of the data (Fig. 4). In the control codend, the mean size of the *Nephrops* caught in the lower compartment was 43 mm CL (range: 21–71 mm), and 45 mm CL (range: 28–72 mm) for those caught in the upper compartment. In the test codend, the mean size of the *Nephrops* caught in the lower compartment was 44 mm CL (range: 25–76 mm). In the upper compartment, only one individual of 36 mm CL was retained (Fig. 4d).

Overall, 91% (CI: 88%–92%) of the fished population of *Nephrops* entered the lower compartment. In the test codend, there was a strong, significant preference for the lower compartment for the size range 25–76 mm CL (Fig. 5a). Given that *Nephrops* was caught in the lower compartment, the probability of being retained through the 60 mm square meshes increased with increasing size up to 69 mm CL and the L50 was 30 mm CL (Fig. 5b). Larger individuals were all retained by the 60 mm square meshes. The retention at the MCRS of 32 mm in Skagerrak and Kattegat was 55% (CI: 8%–76%), and at the MCRS of 25 mm in the North Sea it was 37 % (CI: 5%–59%). Given that *Nephrops* was caught in

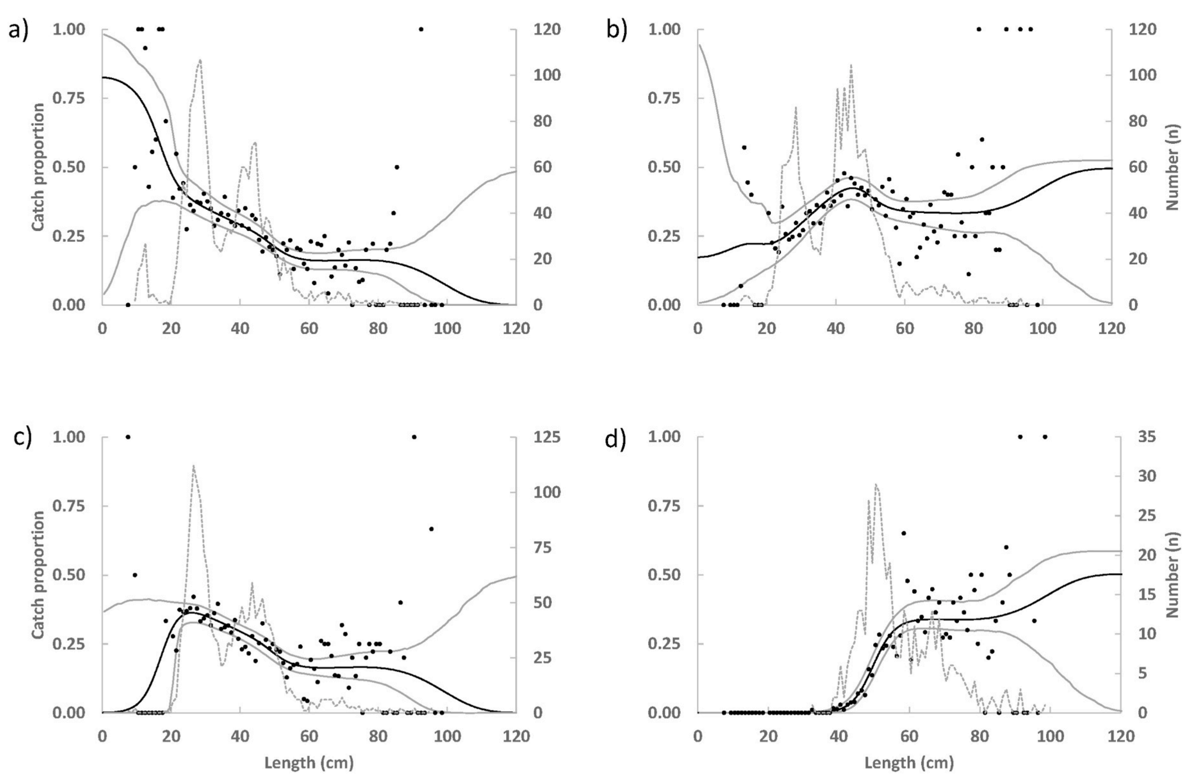

Fig. 2. Length-based catch proportions (black lines) with 95% confidence intervals (grey lines) of the total fished population for cod. The compartment-specific populations are given as dotted lines. Control codend: a) lower compartment (40 mm), b) upper compartment (40 mm). Test codend: c) lower compartment (60 mm), d) upper compartment (120 mm).

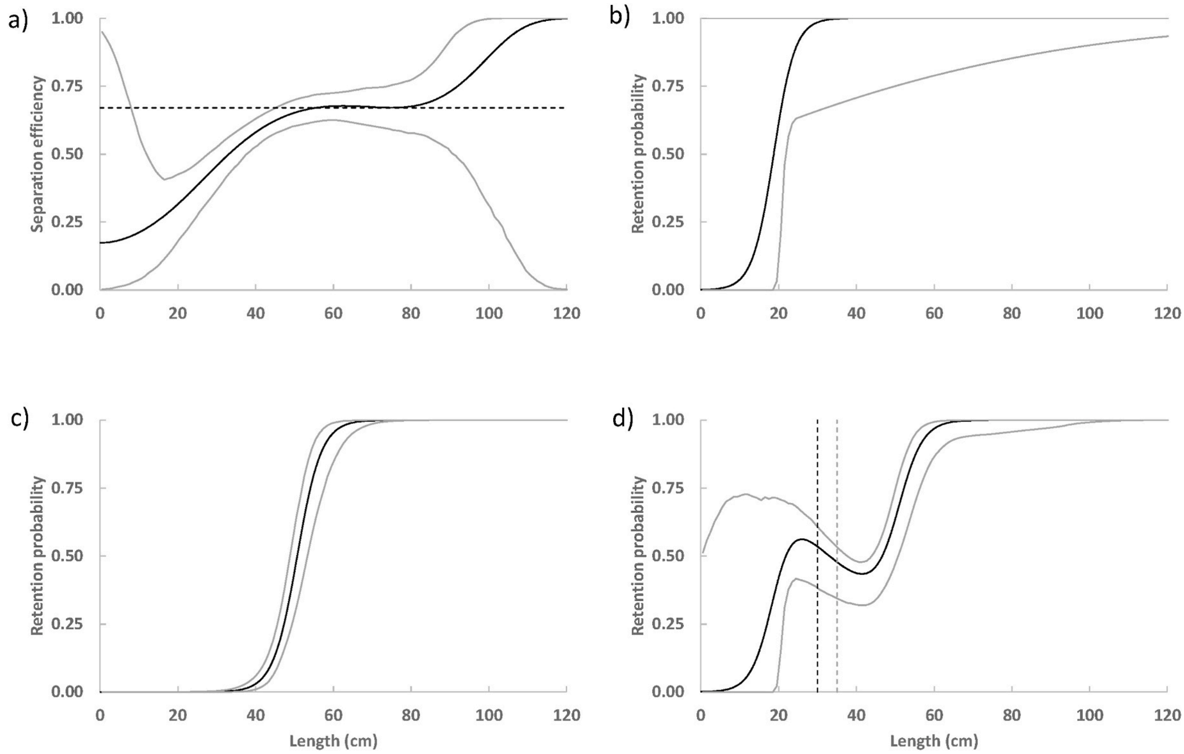

Fig. 3. Cod in the test codend. a) Vertical separation efficiency (black line) with 95% CI (grey lines) and with equal separation according to the relative size of the compartment (horizontal broken line). Selectivity curves (black lines) with 95% CIs (grey lines) for the b) lower compartment (60 mm), c) upper compartment (120 mm), d) combined selectivity of the two compartments with the MCRS of 30 cm for Skagerrak and Kattegat (vertical black broken line), and 35 cm for the North Sea (vertical grey broken line).

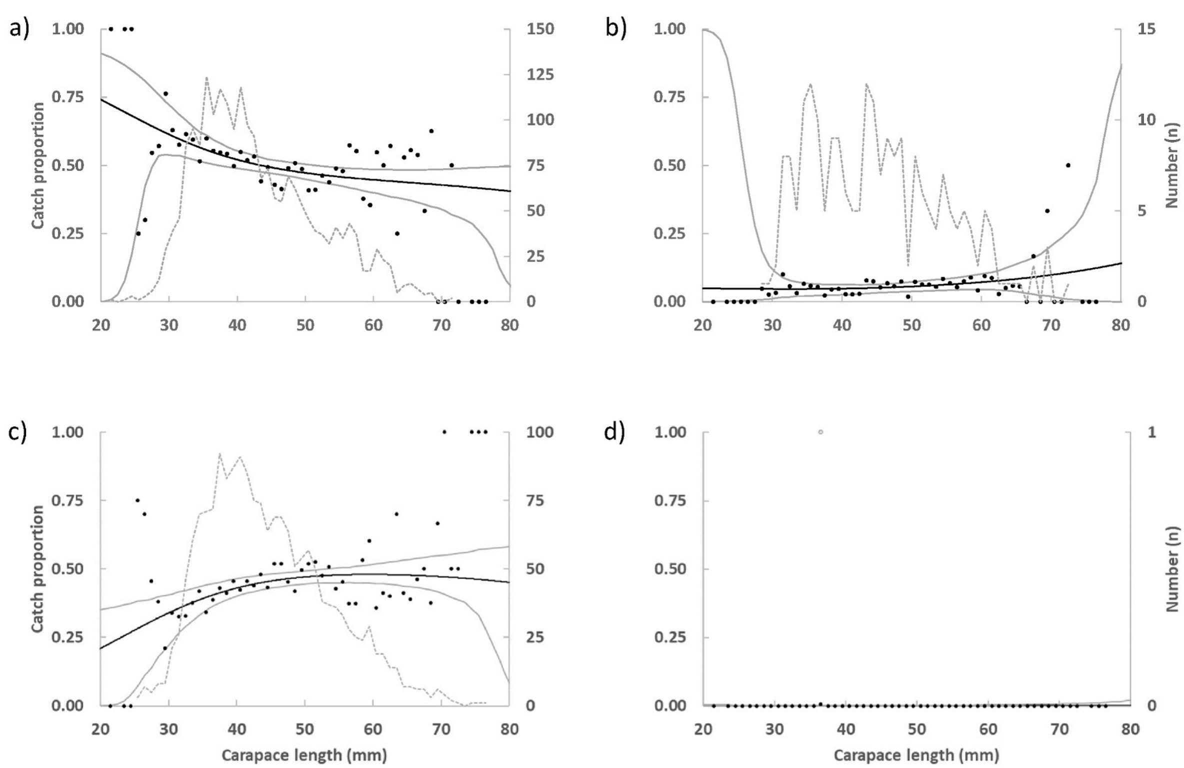

Fig. 4. Length-based catch proportions (black lines) with 95% confidence intervals (grey lines) of the total fished population for *Nephrops*. Control codend: a) lower compartment (40 mm), b) upper compartment (40 mm). Test codend c) lower compartment (120 mm), d) upper compartment (60 mm). The compartment-specific population (dotted lines) is given as a circle for the upper compartment of the test codend as only one individual (36 mm CL) was retained.

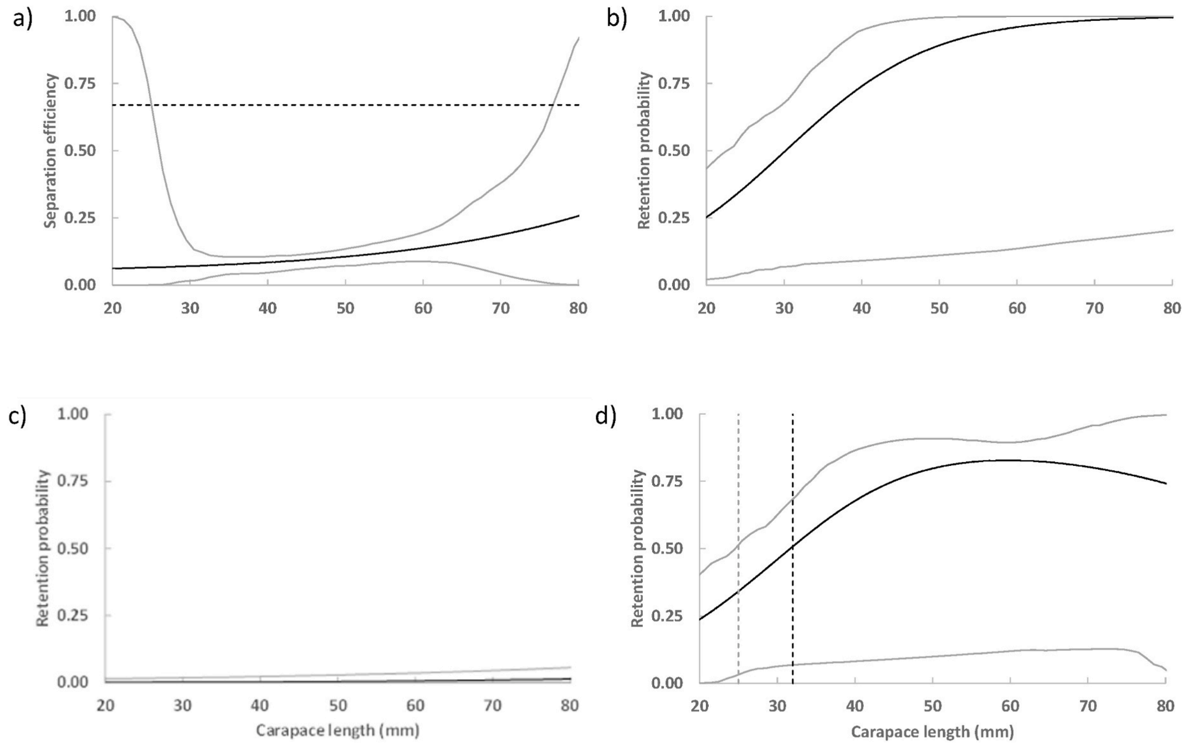

Fig. 5. *Nephrops* in the test codend. a) Vertical separation efficiency (black line) with 95% CI (grey lines) and with equal separation according to the relative size of the compartment (horizontal broken line). Selectivity curves (black lines) with 95% CIs (grey lines) for the b) lower compartment (60 mm), c) upper compartment (120 mm), d) combined selectivity of the two compartments with the MCRS of 32 mm carapace for Skagerrak and Kattegat (vertical black broken line), and 25 mm for the North Sea (vertical grey broken line).

the upper compartment, the probability of being retained by the 120 mm square meshes was very low (Fig. 5c). As a large proportion of the *Nephrops* entered the lower compartment, the combined selectivity for the whole codend was very similar to that of the lower compartment (Fig. 5d).

3.3. Catch indicators

3.3.1. Cod

The catch indicators showed that approximately half of the cod population entering the test codend was retained (Table 4). This was also the result for both the cod catch < MCRS (*nP*-) and ≥MCRS (*nP*+) for the Skagerrak/Kattegat and North Sea areas. In a scenario where the lower codend is left open during fishery, the upper compartment of the test codend would only catch 12% of the cod population entering the codend (Table 4). None or very few of the cod < MCRS would be caught, and the ratio of undersized cod would be 0%, while 17%–20% of cod ≥ MCRS would be caught. In a scenario where the upper codend is left open during fishery, the lower compartment of the test codend would catch less than half (44%) of the cod population entering the codend. More than half of the cod < MCRS and less than 40% of the cod ≥ MCRS would be caught. The ratio of undersized cod would be 9% higher in the North Sea due to the larger MCRS. Approximately one fifth (21.8%) of the cod catch entering the upper compartment was retained in the test codend (Table 4). All or most of the undersized cod escaped while roughly 30% of the cod ≥ MCRS were retained. In contrast, more than 90% of the cod entering the lower compartment of the test codend was retained. Slightly less than that were retained of the cod < MCRS entering the lower compartment, while almost all cod ≥ MCRS were retained.

3.3.2. Nephrops

The catch indicators showed that approximately three-quarter of the *Nephrops* population entering the codend was retained by the test codend (Table 4). Approximately half of the Nephrops < MCRS would be retained in the Skagerrak/Kattegat, while they all would be released in the North Sea. In total 22%–23% of *Nephrops* ≥ MCRS entering the codend would be lost. The ratio of undersized *Nephrops* would be low in both areas. In a scenario where the lower codend is left open during fishery, no *Nephrops* would be caught, thus, if the upper codend was left open, the catch of *Nephrops* would not change (Table 4). All the *Nephrops* entering the upper compartment, except for a single individual > MCRS, were lost. Most of the *Nephrops* entering the lower compartment were retained, especially if they were ≥MCRS. About half of the *Nephrops* < MCRS that entered the lower compartment would be retained in Skagerrak, while none would be retained in the North Sea due to the lower MCRS.

4. Discussion

In mixed fisheries, it is unlikely that a trawl equipped with only one codend mesh type can provide optimal selectivity in all fishing situations. This study has demonstrated an operational design concept, the dual compartment codend, where different groups of catch undergo different selectivity. The gear has applicability in all types of mixed trawl fisheries to accommodate a variety of catch goals among fishers due to the composition and status of their quota portfolio. The selective properties of the two compartments can easily be adjusted by simply replacing the mesh types with ones that give a suitable selectivity for a given mix of species they encounter at the fishing ground. In addition to the operational design concept, an analytical methodology was provided that can evaluate the design concept by quantifying the overall selectivity of the dual compartment codend as well as each step of the selectivity process, i.e., the vertical separation into different compartments and the subsequent selectivity in each compartment. Furthermore, improvement opportunities were identified using catch

Table 4
Catch indicators used to evaluate the test codend in two areas, Skagerrak/Kattegat and North Sea, of different MCRS.

	Cod		*Nephrops*	
	Skagerrak (MCRS: 30 cm)	North Sea (MCRS: 35 cm)	Skagerrak (MCRS: 32 mm)	North Sea (MCRS: 25 mm)
Overall test codend				
nP (%)	55.5 (51.0–60.1)	55.5 (51.0–60.1)	76.6 (69.3–87.8)	76.6 (69.3–87.8)
nP- (%)	53.9 (44.7–65.8)	53.8 (45.9–63.2)	51.0 (23.3–76.6)	0.0 (0.0–0.0)
nP+ (%)	56.2 (50.5–62.8)	56.7 (50.4–63.9)	78.4 (71.1–89.4)	76.8 (71.1–88.9)
dnRatio	30.7 (25.5–36.9)	40.1 (34.5–46.4)	4.3 (1.4–6.9)	0.0 (0.0–0.0)
The other compartment open				
nPT1 (%)	11.5 (8.8–14.4)	11.5 (8.8–14.4)	0.0 (0.0–0.3)	0.0 (0.0–0.3)
nPT1- (%)	0.0 (0.0–0.0)	0.1 (0.0–0.3)	0.0 (0.0–0.0)	0.0 (0.0–0.0)
nPT1+ (%)	16.9 (13.4–20.2)	19.6 (15.9–23.6)	0.0 (0.0–0.4)	0.0 (0.0–0.3)
dnRatioPT1	0.0 (0.0–0.0)	0.2 (0.0–1.0)	0.0 (0.0–0.0)	0.0 (0.0–0.0)
nPT2 (%)	47.0 (43.3–50.2)	47.0 (43.3–50.2)	76.6 (70.9–88.8)	76.6 (70.9–88.8)
nPT2- (%)	53.9 (45.0–65.0)	53.7 (46.2–63.7)	51.0 (20.0–77.3)	0.0 (0.0–0.0)
nPT2+ (%)	39.3 (33.5–44.6)	37.1 (31.0–42.6)	78.4 (72.4–90.6)	76.8 (71.0–88.8)
dnRatioPT2	38.8 (32.6–44.9)	50.5 (45.0–56.7)	4.3 (0.8–6.4)	0.0 (0.0–0.0)
Each compartment				
nT1 (%)	21.8 (16.0–27.4)	21.8 (16.0–27.4)	0.4 (0.0–3.6)	0.4 (0.0–3.6)
nT1- (%)	0.0 (0.0–0.0)	0.2 (0.0–0.7)	0.0 (0.0–0.0)	NA
nT1+ (%)	28.4 (22.5–34.3)	32.0 (25.6–38.6)	0.5 (0.0–3.6)	0.4 (0.0–3.6)
nT2 (%)	93.5 (81.6–107.5)	93.5 (81.6–107.5)	84.6 (78.0–98.5)	84.6 (78.0–98.5)
nT2- (%)	88.7 (70.4–113.9)	91.5 (76.1–110.3)	55.3 (22.2–85.0)	0.0 (0.0–0.0)
nT2+ (%)	96.8 (82.0–112.7)	95.6 (78.6–113.8)	86.6 (79.9–100.3)	84.8 (78.3–98.5)

indicators.

In a case study from Skagerrak and Kattegat using two contrasting mesh types, the codend system was evaluated for its release efficiency of cod and retention efficiency for *Nephrops*, two highly relevant commercial species. The overall selectivity curve for cod, which combined the selectivity of the upper and lower compartments, demonstrated that it is possible in a gear, to obtain a size selectivity that is very different from the sigmoid selectivity curve of a codend having only one mesh type. The new shape was a result of the contrast in mesh size of the upper and lower compartments, and the fact that the proportion of cod that entered the upper compartment and thus got access to the larger meshes, increased for cod up to 44 cm. The 120 mm square mesh netting chosen for the upper compartment efficiently released cod below and just above the MCRS from the gear in accordance with the intention. This may be considered an optimal selectivity if the fisher has a restricted cod quota and only wants to retain the largest, highest priced individuals, but may be far from optimal in other catch goal scenarios. The dual compartment codend then allows tailoring selectivity to a given quota portfolio status and catch composition encountered at any given time. For example, if a large cod quota is available, it may be desirable to retain all individuals above MCRS and so the selectivity of the upper compartment must be restricted, e.g., by replacing the netting in the upper compartment with a smaller mesh netting, which is something that can be done at sea. The 120 mm square mesh gave an L50 of 50 cm. A design guide predicting size selectivity of different mesh types and sizes given for cod in Herrmann et al. (2009) suggest that a 100 mm square mesh gives an L50 of 40 cm and a 90 mm square mesh an L50 of 34 cm that may be more appropriate for the North Sea (MCRS: 35 cm) and Skagerrak/Kattegat (MCRS: 30 cm) areas, respectively. There are available software tools, like FISHSELECT, that can be used to predict the size selectivity of given combinations of mesh size, geometry, and openings if morphology measures of the species has been collected (Herrmann et al., 2009; Frandsen et al., 2010; Krag et al., 2011; Sistiaga et al., 2011; Tokaç et al., 2016). Due to the current poor status of the cod stocks in the Skagerrak/Kattegat and North Sea areas (ICES, 2020b,c), a more likely scenario may be to avoid all cod bycatch, e.g., by leaving the upper compartment open, to allow continued fishing for *Nephrops*. However, this will negatively affect catches of other important bycatch species, such as haddock or plaice. To preserve large, high fecundity cod for stock conservation, the selectivity curve may further be adjusted in a stepwise selectivity process where these large individuals are sorted out of the gear prior to the codend selectivity of the individuals smaller than the MCRS (Stepputtis et al., 2016).

The overall selectivity curve for *Nephrops* was similar to that of the lower compartment as *Nephrops* entering the upper compartment were lost through the 120 mm square meshes. The 60 mm square mesh netting of the lower compartment was originally chosen to release individuals under the old minimum landing size of 40 mm CL in Skagerrak and Kattegat. It was therefore efficient in releasing *Nephrops* below the current reference sizes, i.e., 63% loss at 25 mm CL (MCRS in the North Sea) and 45% loss at 32 mm CL (MCRS in Skagerrak/Kattegat). The size groups just above the MCRS were also efficiently released and added to the 9% loss of individuals larger than the reference size to the upper compartment. In comparison, the loss of 25 mm CL in a 90 mm diamond mesh codend is reported to be 18%, and 9% for 32 mm CL (Frandsen et al., 2010). The L50 for the 60 mm square mesh netting is 30 mm CL and reducing the mesh size would reduce the L50. There is currently not a design guide available for smaller square mesh sizes, but an appropriate mesh size for the different areas could be modelled based on data collected using the FISHSELECT methodology (Frandsen et al., 2010). The selection curve of *Nephrops* is typically characterized with a wide selection range, likely due to differences in the escape efficiency of the variety of orientation modes *Nephrops* may meet with the netting (Frandsen et al., 2010) as well as variations in the mesh openness (Herrmann and O'Neill, 2005). Efficient retention of individuals at the MCRS thus implies less efficient release of the size groups just below the MCRS, but this may be optimised using fixed meshes (Bak-Jensen et al., 2022). It needs to be emphasized that the scientific basis for making management decisions related to selective gears is limited by the uncertainty in the estimation of the mean selectivity curves. A high survival exemption from the landing obligation in these areas also allows fishers to discard *Nephrops* smaller than the reference size (EU, 2020).

The efficiency of the codend system to release cod and at the same time efficiently retain the valuable catches of *Nephrops* is highly dependent on how well these species can be separated from each other and led into different compartments. Almost half (47% in numbers) of the fished population of cod were caught in the lower compartment where the probability of escaping through the small meshes is low (2% for 30 cm cod, MCRS in Skagerrak/Kattegat; 0% for 35 cm cod, MCRS in the North Sea; L50 of 18 cm) unless they were very small. In a scenario of low cod quotas, this implies a risk of cod choking the fishery for *Nephrops*. Furthermore, the high release of the *Nephrops* that unintentionally entered the upper compartment (9% of the fished population, typically the largest individuals) implies a suboptimal capitalization of the quota both in terms of catch value and fuel consumption per unit quota. In this study, catch proportions are given in numbers and not in weight as the quotas. As smaller individuals weigh less that larger individuals, the selective performance (given as proportions) of the divided codend will be higher if based on weight. The duration of the hauls was kept shorter than commercial hauls to prevent the risk of overfilling and so mixing the catch from the two compartments. This can be prevented by extending the length of the compartments (Melli et al., 2019).

The proportion of fish entering the different compartments may be altered merely by changing the height of the separation panel (Main and Sangster, 1982; O'Neill and Summerbell, 2019). This solution may however not seem promising in this case considering that the lower compartment was only 30 cm high. Thus, there would be a risk of losing a higher proportion of *Nephrops* to the upper compartment if the hight of this compartment reduced, and the high preference of cod for a low vertical distribution may still lead to a large proportion being caught in the lower compartment (Karlsen et al., 2019). Rather, it may be necessary to change the vertical distribution of cod. In Skagerrak, Melli et al. (2019) found that it is possible to affect which compartment small cod enters despite that their swimming capacity is inferior to that of larger individuals. They were able to raise small cod (7–16 cm) into the upper compartment with a chain curtain attached to the upper part of the frame at the entrance of the lower compartment in a gear similar to that used in our study. The chain curtain did not affect the distribution of *Nephrops* into the two compartments. Fixed and freely moving float ropes have proven to increase the escapes of cod (20–40 cm and 33–48 cm, respectively) through an escape panel placed in the upper panel of a codend implying that the vertical behaviour of cod was actively changed (Herrmann et al., 2015; Krag et al., 2017). The size range of these cod were within the size range (8–44 cm) that preferred entering the lower compartment. It has not been tested if freely moving float ropes may affect the vertical distribution of *Nephrops,* but fixed float ropes did not affect the catch of *Nephrops* (Krag et al., 2017), and rising float-lines have increased the amount of small *Nephrops* (17–27 mm CL) entering the lower compartment (Melli et al., 2019). Large *Nephrops* have not shown to respond to mechanical stimulators. Instead, the proportion that are being lost to the upper compartment may be reduced using artificial light, e.g., green LED lights (40–55 mm CL, Melli et al., 2018) or luminous netting (56–64 mm CL, Karlsen et al., 2021). Active stimulation devices such as chain curtain and float ropes as well as artificial lights can be easily attached and detached to the gear.

Simple ways of influencing the vertical separation of species coupled with the possibility in a dual compartment codend to quickly change netting types of a compartment at sea, introduce a more complex selectivity profile as well as the possibility to adjust the species and size selectivity to the catch profile encountered. The importance of such flexibility on the fishing ground is expected to increase in the future to enable fishers to better meet their catch goals and comply with management plans that sharpens the requirements on bycatch mitigation. As more complex trawl designs are being tested to accommodate the complexity of fishing on a mix of species with different morphologies, sizes, and behaviour, simple solutions may be easier and safer to handle under various conditions at sea (Sistiaga et al., 2018). Furthermore, if efficient in reducing bycatch without loss of catch value, simple gear designs may facilitate uptake by the industry (Broadhurst, 2000; Catchpole and Revill, 2008). The simplest combination of different codend constructions and catch separation devices that maximises the reduction of unwanted catch in a mixed species scenario can theoretically be explored following Melli et al. (2020). Similarly, the performance of the multi-selective design concept should be explored when including other commercial bycatch species.

Although flexibility in gear modification may facilitate the implementation of increasingly ambitious management plans, such as the landing obligation under the Common Fisheries Policy, the technical regulation remains to be a limitation. In regions like the EU, where it is only permitted to use a few designs in a management area, the utilisation of other designs such as the current version of the dual compartment codend is prevented. If gears providing a differential selectivity were allowed, unwanted catch may be substantially reduced, especially in highly exploited areas where they are using small codend meshes in the trawls like the Mediterranean (Mytilineou et al., 2023). Recently, "dynamic ocean management," has been suggested as a management tool to provide fishermen with near real-time information on fishing conditions, for example species distribution, oceanographic conditions, and observer data, to reduce unwanted bycatch risks while fishing for target species (Lewison et al., 2015; Maxwell et al., 2015; Townsend et al., 2019). Similarly, new technologies for monitoring and recording species and size compositions during fishing (real-time camera observations, Sokolova et al., 2022) or onboard the vessel (REM, van Helmond et al., 2020) are entering fisheries in several countries and may bring a solution to how compliance to the management plans can be controlled. As REM accounts for the entire catch, the fishers are made responsible for the conducted catching process. Such technology can, in addition to control, be used to relax the technical regulation and clear the way for the use of more flexible gear designs in the future. In a controlled setting, selective fishing gears that can be adjusted or changed according to the given conditions at sea will become a much stronger management tool than what is the case today where one gear is expected to fit all conditions in a given fishery or management area.

CRediT authorship contribution statement

Junita D. Karlsen: the conception and design of the study, or, Funding acquisition, of, Data curation, or, Formal analysis, and interpretation of, Data curation, Writing – original draft, the article or revising it critically for important intellectual content, final approval of the version to be submitted. **Ludvig Ahm Krag:** the conception and design of the study, or, Funding acquisition, of, Data curation, or, Formal analysis, and interpretation of, Data curation, Writing – original draft, the article or revising it critically for important intellectual content, final approval of the version to be submitted. **Bent Herrmann:** the conception and design of the study, or, Funding acquisition, of, Data curation, or, Formal analysis, and interpretation of, Data curation, Writing – original draft, the article or revising it critically for important intellectual content, final approval of the version to be submitted.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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