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Improving the size- and species selectivity of COD (*Gadus morhua*) in demersal mixed-species trawl fisheries

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Improving the size- and species selectivity of cod (*Gadus morhua*) in demersal mixed-species trawl fisheries

*A dissertation submitted in partial fulfilment of the requirements for
obtaining the degree of Doctor of Philosophy*

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May 2009

Preface

The present dissertation is submitted in partial fulfilment of the requirements for obtaining the Doctor of Philosophy (Ph. D.) degree. The dissertation consists of a review and four supporting papers. Three papers are published and one is submitted for publication.

I wish to express my sincere thanks to my supervisors: Dr. Niels Madsen and Dr. Bent Herrmann from Danish Technical University, Aqua (DTU Aqua) and to Associate Professor Dr. Jens-Ole Frier, Aalborg University. Further I wish to thank Rene Holst, Rikke P. Frandsen, Dr. Bo Lundgren (DTU Aqua) and Kurt Hansen, SINTEF - North Sea Science Park, Hirtshals for good collaboration throughout this process. Dr. Bo Lundgren and Junita D. Karlsen are gratefully acknowledged for improving the English on the draft version of the present text.

Finally, I wish to thank my wife, Junita D. Karlsen and my two wonderful children Amanda and Benjamin for putting things in perspective.

The financial support granted by the European Commission and the Danish Ministry of Food, Agriculture and Fisheries to conduct the research described in the supporting papers is gratefully acknowledged.

Hirtshals, May 2009.

Ludvig Ahm Krag

The Royal Commission on Trawling (1883-85) recommended that the British government allocated money to find out how fishing gear worked and what effects they had on stocks and seabed; more than a century later we are asking similar questions for similar reasons.

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List of papers

Krag, L.A., Frandsen, R.P., Madsen, N., 2008. Evaluation of a simple means to reduce discard in the Kattegat-Skagerrak Nephrops (*Nephrops norvegicus*) fishery: Commercial testing of different codends and square-mesh panels. *Fisheries Research*, 91: 175-186.

Paper 2

Herrmann, B^{*}, Krag^{*}, L.A., Frandsen, R. P., Madsen, N., Lundgren, Stæhr K-J., 2009. Prediction of selectivity from morphological conditions: Methodology and a case study on cod (*Gadus morhua*). *Fisheries Research*, 97: 59-71.

(^{*}) = equal authorship.

Paper 3

Krag, L.A., Holst, R., Madsen, N., Hansen, K., Frandsen, R.P., xxxx. Selective haddock (*Melanogrammus aeglefinus*) trawling – avoiding cod (*Gadus morhua*) bycatch. Submitted to *Fisheries Research*.

Paper 4

Krag, L.A., Holst, R., Madsen, N., 2009. The vertical separation of fish in the aft end of a demersal trawl. *ICES Journal of Marine Science*, 66: 772-777.

Paper 1 and 2 are reprinted from *Fisheries Research*.

Paper 4 is reprinted from *ICES Journal of Marine Science*.

The papers are referred to by their numbers.

Dansk resume

Bestandene af torsk i Kattegat-Skagerrak og i Nordsøen har det sidste årti været på et kritisk lavt niveau. Der er i samme periode indført en række forvaltningstiltag for at beskytte og bidrage til at genopbygge disse bestande af torsk. De fleste fiskerier i Kattegat-Skagerrak og i Nordsøen er blandet-arts-fiskerier hvor flere forskellige arter fanges sammen. Bundtrawl er den mest udbredte form for fiskeri i Danmark målt i både fangst-værdi og volumen, samt den fiskeri form med højest discard af juvenile fisk, herunder torsk. Denne Ph.d. består af en sammenfatning og 4 artikler og vil fokusere på at forbedre selektionen af torsk i bundtrawl.

Der er generelt to hovedteknikker hvorved fisk kan undslippe fra et fiskeredskab. Den første teknik involverer en mekanisk sorteringsproces baseret på fiskens størrelse, mens den anden teknik er baseret på udnyttelse af arts-specifikke adfærdsmønstre under fangst processen. I artikel 1 beskrives et forsøg med kvadratmaskepaneler (KMP) hvor effekten af et KMP, placering af et KMP, maskestørrelse i et KMP samt at anvende en større maskestørrelse i fangstposen undersøges med henblik på at forbedre størrelsesselektionen af torsk i jomfruhummerfiskeriet. I artikel 2 beskrives en ny metode, værktøjer og software, der er udviklet og anvendt til at måle de morfologiske parametre der afgøre hvorvidt en torsk kan penetrere forskellige masketyper, -størrelser og -åbninger. Resultaterne viser, at de morfologibaserede simuleringer af størrelsesselektionen af torsk kan anvendes til at forklare størstedelen af den variation i selektionsparametrene, der observeres både mellem forskellige slæb og indenfor det enkelte slæb. Denne metode kan endvidere forudsige selektionsparametrene (L50 og SR) for torsk for forskellige masketyper, -størrelser og -åbninger. Artikel 3 beskriver et nyt trawl-design, der adskiller torsk fra målarten kuller ved at udnytte de to arters forskellige adfærd i fangstsituationen. Redskabet er baseret på torsks tendens til at svømme meget tæt på havbunden, mens kulleren svømmer højt over havbunden i det de kommer ind i selve trawlen. Dette udnyttes ved at hæve trawlens fiskeline over bunden således at torsken kan undslippe mens kulleren tilbageholdes. Størstedelen af de arter der har stor økonomisk betydning for dansk fiskeri med bundtrawl, her i blandt torsk, går i midlertidigt alle ind i et trawl meget tæt på havbunden. Artikel 4 beskriver et forsøg hvor den rumlige adfærd af fisk undersøges tilbage i trawlens forlængerstykke med en vertikal delt ramme med henblik på at adskille arter der ikke kan adskilles fremme i trawlen. Endvidere blev en modificeret skilleramme med en simpel mekanisk stimulus anvendt for at undersøge hvorvidt den observerede vertikale fordeling af fisk kan påvirkes, således at torsk bedre kan adskilles fra andre arter længere tilbage i trawlen.

Der er betydelige forskelle i morfologi og adfærd mellem de mange kommercielt vigtige arter der fanges i de forskellige blandede fiskerier, hvor også forskellige redskabsdesign

benyttes. Dette gør det særdeles vanskeligt at udvikle *et* redskabsdesign der kan reducere fangsten af torsk effektivt og samtidigt tilbageholde de landbare arter og størrelser effektivt. For at kunne optimere dette forhold bør selektive løsninger være specialiseret til specifikke fiskerier. Artikel 1 og artikel 3 viser specifikke eksempler på hvordan henholdsvis størrelses- og artsselektionen for torsk forbedres. Artikel 4 viser at den vertikale fordeling af torsk og andre arter kan ændre sig langs trawlens langsgående akse, samt at fisks vertikale præferencer i trawlen kan påvirkes med simple stimuli. Metoden, der beskrives i artikel 2, åbner nye muligheder for at studere og forudsige størrelsesselektionen i fiskeredskaber på en systematisk måde baseret på fiskens morfologi og formen på de masker som fisken præsenteres for under fiskeri. Trawl-design kan hermed teoretisk optimeres før de afprøves under kostbare og ressource krævende forsøg til søs.

Artikel 1, 2, og 4 er publiceret i videnskabelige tidsskrifter, og artikel 3 er indsendt med henblik på publicering i et videnskabeligt tidsskrift. Sammenfatningen vil mere generelt og bredere belyse selve fangstprocessen, der er grundlaget for selektionsprocessen. Sammenfatningen vil videre belyse eksisterende metoder og viden indenfor både størrelsesselektion og artsselektion, der er relevant for bundtrawlfiskerier i Kattegat-Skagerrak og Nordsøen hvori torsk fanges.

English summary

For the last decade, the Kattegat-Skagerrak and the North Sea cod stocks have been at a critically low level. Several management initiatives were introduced to protect and aid the recovery of these cod stocks. Most fisheries in these areas are conducted in a multispecies setting, where several different species, including cod, are caught together. Demersal trawling is the predominant fishing method in Denmark, as measured by both catch value and volume. Demersal trawls also account for the highest discard rates of juvenile fish, including cod. The focus of this work was on improving the selectivity of demersal trawling with regard to cod. This Ph.D. thesis consists of a review and four supporting papers (1-4).

Two main techniques are used to aid fish in escaping from fishing gear. The first technique involves a process of mechanical sorting based on fish size and the second is based on the use of species-specific behaviour patterns. Paper 1 describes an experiment in which square mesh panels (SMPs) were used to study what effects the SMP have, the position of the SMPs in the extension and codend, of the mesh size of the SMP, and of the general increase in the codend mesh size. The goal of this study was to improve the size selection for cod in the fisheries directed towards *Nephrops*. Paper 2 describes a new methodology, tools, and software that have been developed and used to measure the morphological parameters that determine the ability of cod to penetrate different mesh types, sizes, and openings. The results show that the morphology-based simulations of size selectivity of cod can be used to explain a large part of both the within-haul and the between-haul variations previously reported from sea trials. The method can further predict the selection parameters (L50 and SR) for cod for different mesh types and sizes. Paper 3 describes separation of cod from haddock based on differences in behaviour between the two species. The design of the gear used in this study is based on the tendency of cod to stay close to the seabed and of haddock to rise as they enter the trawl; the gear, therefore, was designed to keep the fishing line raised above the seabed to avoid catching cod. The majority of the economically important species in the Danish demersal fisheries, including cod, all enter the trawl low and close to the seabed, thus behavioural-based separation of cod and the other species is not possible at the mouth of the trawl. Paper 4 describes an experiment in which behaviour was studied in the extension piece of a demersal trawl equipped with a vertical separator frame. A second vertical separator frame with raising bars was used to determine if the observed vertical distribution could be stimulated with the aim of separating species.

The morphology and behaviour of cod and other commercially important species in relation to fishing gear and the numerous different fisheries and gear designs in which cod are caught make it very difficult to develop a universal design that can substantially reduce the catch of cod without simultaneously reduce the catch of the target species. To optimise the trade-off between discard and loss of marketable catch, solutions have to be specific to particular fisheries or populations of fish. Papers 1 and 3 provide specific examples of how size- and species selection, respectively, has been improved for cod. Paper 4 demonstrates that the vertical behaviour of cod and other species can change along the longitudinal axis of a trawl and that these vertical preferences can be stimulated by simple means. The new methodology described in Paper 2 offers new possibilities for studying and predicting size selection in a systematic way based on the morphology of fish and the shape of the mesh with which the fish is presented. New gear designs can thereby be optimised theoretically before being subjected to expensive and time-consuming sea trials.

Papers 1, 2, and 4 have been published in scientific journals and Paper 3 has been submitted to Fisheries Research. This review will take a broader perspective and will examine the capturing process, which is the basis for the selection process. Moreover, it discusses the existing methods and knowledge in the fields of size selection and species selection relevant to the demersal trawl fisheries in the Kattegat-Skagerrak and the North Sea where cod is caught.

1. Introduction

Commercial fishing gears have been refined over time to maximize catch. Concerns about incidental and discarded catches of non-target species or undersized individuals that are captured during fishing have not followed the past's development of fishing gear. However, interest in the topic from research and management perspectives has increased over the last two decades as fisheries throughout the world begin to reach their limits of exploitation (Moore and Jennings, 2000). The Food and Agricultural Organisation of the United Nations (FAO) has estimated that between 18 and 40 million tonnes of fish, corresponding to 20–40% of the production of the world's marine fisheries, are discarded every year, and studies of various EC fisheries have estimated discard rates of a similar order of magnitude (Anon., 1994). The definition of bycatch varies among countries and researchers (Alverson et al., 1994), but herein discards are defined as the proportion of the catch of fish or crustaceans that is not retained on board (i.e., returned to the sea) during commercial fishing operations.

If discarded fish could survive the catch and release ordeal, then no real problem would exist. However, biological research has indicated that discard mortality rates for most species brought onboard are very high, even if the fish is still alive when first discarded (Evens et al., 1994). For many commercial species, such as cod (*Gadus morhua*), flatfishes, haddock (*Melanogrammus aeglefinus*), and whiting (*Merlangius merlangus*), the discard mortality rate is estimated to be 90–100% (Evens et al., 1994). The total annual quantity of discards discharged into the North Sea is estimated to be 800.000–950.000 tonnes (Garthe et al., 1996; Tasker et al., 2000). This discard consists largely of juvenile fish of commercial species and arises mostly from the European roundfish, flatfish, and *Nephrops* (*Nephrops norvegicus*) demersal fisheries (Catchpole et al., 2005). In the North Sea, the demersal roundfish trawl fishery discard proportions in numbers caught are estimated to be 20–48% for cod, 30–41% for haddock, and 51–65% for whiting (Cotter et al., 2002). These discard levels can vary substantially between years and especially between different fisheries (Graham et al., 2007). Similar levels of discard occur in the Danish demersal fleet in the North Sea. This discard represents inefficient exploitation of marine resources and a potential loss of revenue for the industry. Discard also undermines quota policies, as discarded specimens are not counted in the quotas.

In general, fishing gear can be categorized as passive or active. Towed gear such as the trawl, the Danish seine, the Scottish seine, and the purse-seine are examples of active gear, whereas passive gear include gill nets, trammel nets, baited hooks, and a large variety of traps and pots. The Danish fleet operating in the demersal fishery includes primarily trawlers and gill and

trammel netters. The larger vessels are primary trawlers where the gill- and trammel-netters primarily are conducted from the smaller vessels in the fleet. The predominant fishing method in the Danish demersal fisheries as measured in catch volume is trawling (Andersen et al., 2005). Three different types of trawling are used in the Kattegat-Skagerrak and the North Sea area; otter board trawling, pair-trawling, and beam trawling. In pair trawling, two vessels are used to spread one trawl during fishing. A beam trawl has a fixed opening and geometry determined by the beam and the trawl head. In otter board trawling, otter boards are used to obtain the geometry of the trawl (Fig. 1). Most otter trawlers today operate two trawls at the same time using one towing system, but otter trawls can be fished in multirig systems with up to eight trawls towed simultaneously. At present, the otter trawl is the all important trawl type used in the Danish fisheries, both in industrial fisheries and in the fishery for species for direct human consumption. Therefore, this thesis focused on the design and properties of demersal otter trawls.

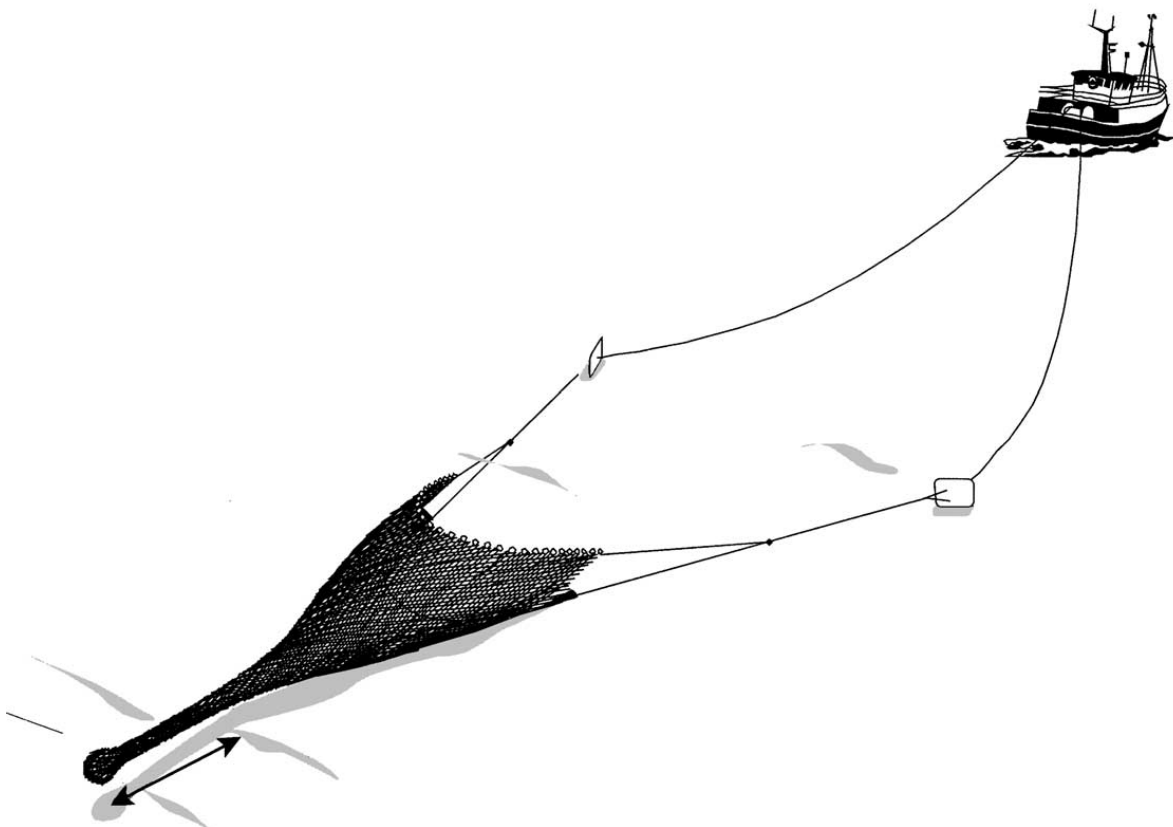


Fig. 1. Demersal trawl fishing with otter-boards. The arrow marks the trawl's codend. (Crown copyright from Marine Scotland – Science.)

In the North Sea and neighbouring waters, cod stocks have declined drastically over the last two decades. Annual landings of cod in the North Sea alone have declined from an average

of around 250.000 tonnes between 1965 and 1985 to around 50.000 by 2006 (Fig. 2) (ICES, 2008). During the last ten years the North Sea cod stock has decreased to a historically low level due to the combined effects of fishing and changing climatic conditions (O'Brian et al., 2000; Beaugrand et al., 2003; ICES, 2006). The stock has exhibited changes in spatial distribution and is now distributed more northerly than before (Perry et al., 2005; Rindorf and Lewy, 2006). The International Council for the Exploration of the Sea (ICES) indicated that reductions in fishing mortality for North Sea cod were necessary to conserve these stocks. Reductions were required for both juveniles and adults to allow the cod stocks to recover. ICES pointed out that the required reductions in fishing mortality cannot be achieved by a reduction in the total allowable catch (TAC) alone because of the considerable bycatch of cod in the fisheries for other roundfish and flatfish species.

Improving the species selectivity or the size selectivity of the fishing gear is an obvious way to try to reduce the discard and improve the yield in a fishery. ICES reported that the yield for several fisheries could be increased by delaying capture until fish have reached a larger size (ICES, 2003). Great effort has been put into developing and testing more selective gear designs. The demersal trawl fisheries in the Kattegat-Skagerrak and the North Sea area can be characterised as mixed-species fisheries because several different species are caught together. The classic mixed-species fishery problem of how to restrict fishing for one or more species without restricting fishing of other species has complicated the development of more selective fishing gear designs for use in these areas. Stocks harvested together may be at a very different status levels relative to safe biological limits, and such a scenario requires different harvest strategies within the same fishery (Kell et al., 2004). In the absence of an accepted approach to providing mixed-species TACs, the European Commission has been seeking to ensure the recovery of the North Sea cod stock through other measures. Notably, the agreed TAC for 2003 was decreased to a level consistent with a 65% reduction in fishing mortality, but for the first time restrictions on fishing effort, in terms of gear type and mesh size categories, also were introduced (Reeves et al., 2008).

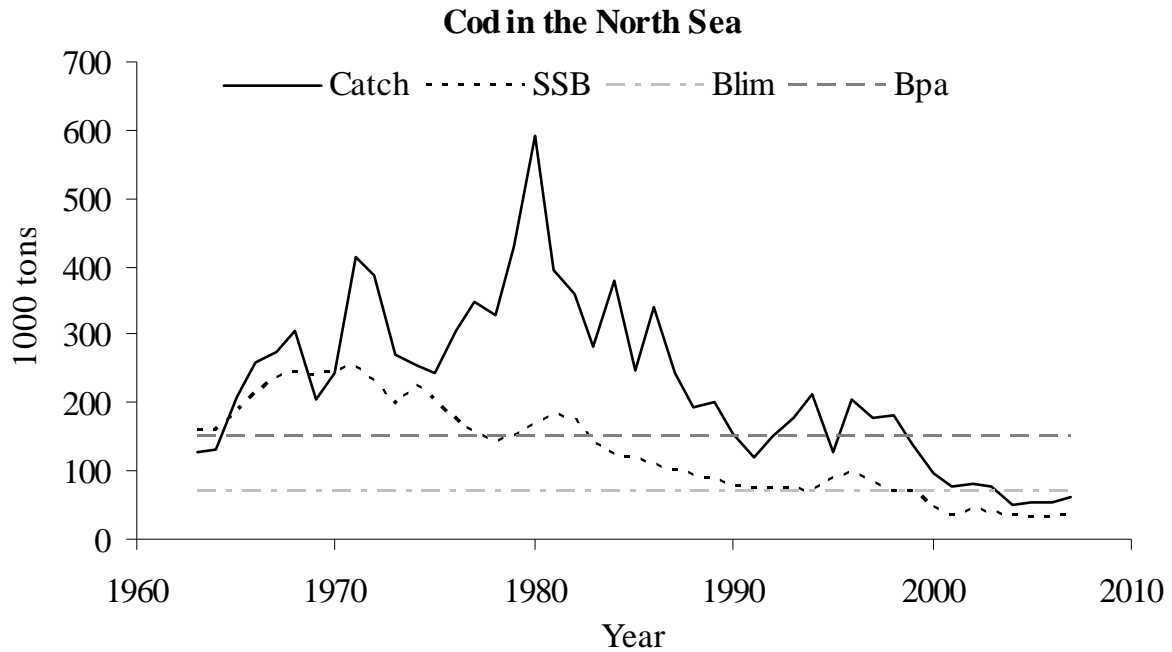


Fig. 2. Historical landings and size of the spawning stock biomass (SSB) for cod in the North Sea. The Biological reference points, Blim (limit spawning stock biomass) and Bpa (precautionary approach spawning stock biomass) are also indicated. For further details, see ICES (2008).

The objectives of this Ph.D. research were to conduct experimental fishing trials, fish behaviour studies, theoretical research, and method development to examine and improve the size- and behavioural-based species selection of cod and other species relevant to the Danish demersal trawl fleet. The work primarily focused on cod, although several other economically important species were included in the practical experiments, as they constitute the catch value in the specific fisheries. The behavioural-based method, tools, and software presented for cod can be adapted and applied to other species.

2. Catching fish with a trawl

2.1 The catching process

Fish are not passively sieved from the sea by a trawl but instead react in quite subtle ways to the different components of the fishing gear. Sounds (including low-frequency pressure variations) from the fishing process draw the attention of the fish long before they can see the gear (Wardle, 1989). Gadoids may begin to dive about 15 minutes before the vessel passes them and show strong herding in front of the trawl warps (Handegard and Tjøstheim, 2005). When a fish is within visual proximity of the fishing gear its behaviour is primarily determined by visual stimuli (Wardle, 1989). The herding process, in which fish are funnelled into the area swept by the trawl netting, begins when fish are in close proximity of the trawl doors. Fish will avoid the trawl doors

by swimming near but in visual contact with the doors, known as the *fountain manoeuvre* (Wardle, 1993). Once fish have passed the trawl doors, it is believed that visual signals provide the directional information towards the trawl mouth for both flatfish and roundfish. Fish are guided into the gear by the trawl otter boards, sweeps, bridles, and netting of the forward parts of the trawl, and as they tire they pass back through the net, keeping clear of the netting until they reach the codend (the rearmost part of the trawl) (see Wardle, 1993). Throughout this process, there is nothing to encourage the fish to pass through the meshes (Glass et al., 1995); on the contrary, fish appears to avoid the netting (Wardle, 1993; Glass et al., 1995). The netting part of trawl is conical and the catch is funnelled towards the codend. The catch accumulates in the codend, where most of the size selection occurs (Beverton, 1963). Underwater observations have shown that the escapement of small fish primarily occurs through the few rows of open meshes just in front of the catch accumulation (Main and Sangster, 1981, 1983, 1991; Wileman et al., 1996; O'Neill et al., 2003). The ability of a fish to avoid capture by a demersal trawl is related to its swimming capability, manoeuvrability, swimming endurance, and behaviour strategy. Several intrinsic factors, such as fish size, age, and physiological condition, and extrinsic factors, such as ambient light intensities and temperature, can effect swimming capability and hence capture success (Walsh and Hickey, 1993; Winger et al., 1999).

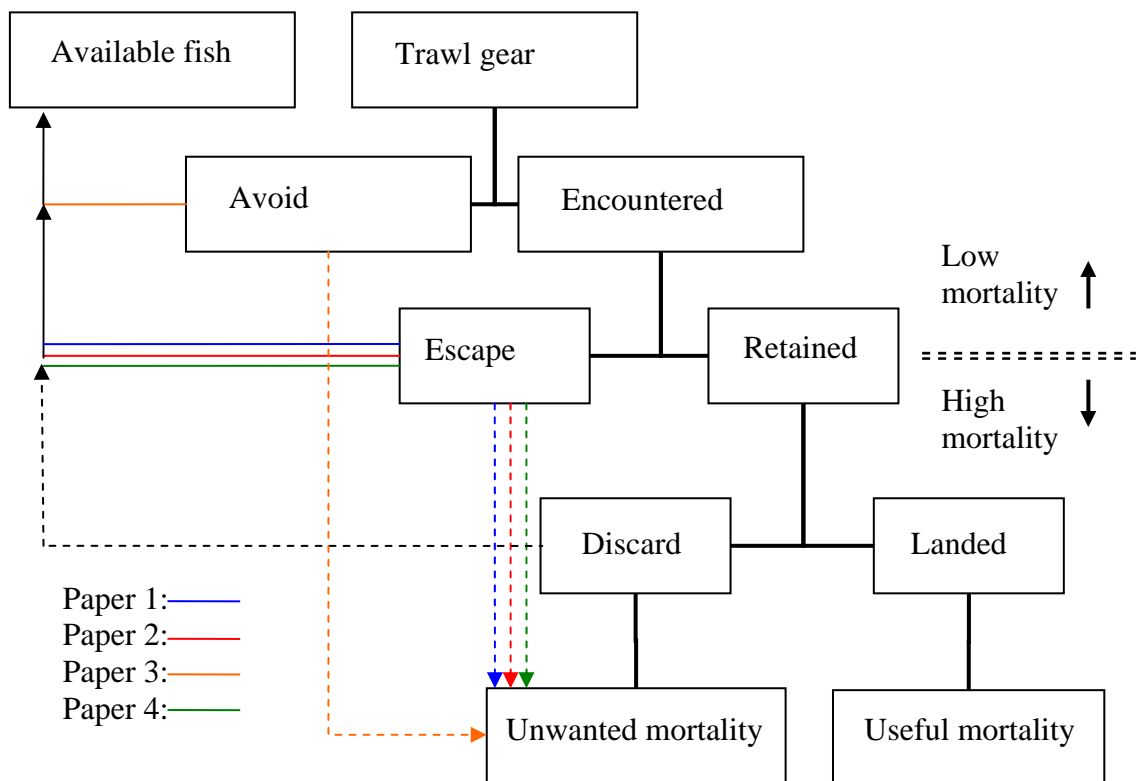


Fig. 3. A simple flow-charge of the capturing process showing all the main selectivity processes. The thin solid shows the most likely fate of escaping fish where the broken line shows a possible by less likely fate of escaping fish. Different colour codes on the left side of the figure mark which part of the capturing process Paper 1-4 focus on. Sizes and species of fish that manage to escape the fishing gear during the first stages in the capturing process shown in the upper half of the figure will have a high survival rate. This is in contrast to the following stages in the lower half which occurs onboard the vessel and therefore results in a high mortality. The outcome of the capturing process is favourable when fish are either landed for human consumption (useful mortality) or when the fish survive the encounter with the fishing gear and are returned to the stock (available fish). If fish however die without being beneficial to the yield of the fishery the outcome is unfavourable. (Modified from Dickson et al., 1995.)

A simple flow-charge of the capturing process is shown in Fig. 3. All main selectivity processes are shown in this figure. Different colour codes on the left side of the figure mark which part of the capturing process Paper 1-4 focus on. The outcome of the capturing process is favourable when fish are either landed for human consumption (useful mortality) or when the fish survive the encounter with the fishing gear and are returned to the stock (available fish). If fish however die without being beneficial to the yield of the fishery the outcome is unfavourable.

2.2 Trawl designs and target species

The trawls used in Kattegat-Skagerrak and the North Sea and in most parts of the world are primarily made from netting that has diamond-shaped meshes. The trawl designs used in the Danish fleets range from small, low headline height trawls specialised to catch *Nephrops* to large and high headline whitefish trawls used to target haddock and saithe (*Pollachius virens*). The design of the trawl depends on the target species and their avoidance behaviour during the capturing

process. The target species' avoidance behaviour affects both the design of the netting part of the trawl and the sweeps, bridles, and ground gear. The relative size of the gear depends on the propelling power of the vessel, which in general depends on the vessel size. Most demersal trawl fisheries that catch fish for human consumption in the Kattegat-Skagerrak and the North Sea are conducted in a multispecies setting, where gadoids, flatfish, *Nephrops*, and monkfish are caught together due to their temporal sympatric abundance on the fishing grounds (Andersen et al., 2005). Cod are caught by virtually all types of demersal gears, including beam trawls, otter trawls, seine nets, gill nets, and long lines. In some of these fisheries cod is considered to be a bycatch, whereas others are directed mainly towards cod (ICES, 2008). The trawl designs often used in these mixed-species fisheries are combined fish and *Nephrops* trawls called *combi-trawls*, and they are designed to catch most of the species that contribute significantly to the total catch value. These designs are not optimised towards a single species but more towards a maximum total catch value in relation to some population expectations. The fishing vessels operating in these fisheries are very diverse in terms of rigging used and fishing strategy and quota rights, and the quantities of cod caught can vary substantially. In some fisheries in some seasons almost no cod are caught, whereas the catch in other fisheries may be substantial. In a mixed-species fishery directed towards *Nephrops*, like that described in Paper 1, *Nephrops* and cod are the most important species economically, but the value of the remaining several species constitutes about 30% of the total catch value.

Several different species are important in the Danish demersal fishery. In the North Sea, plaice (*Pleuronectes platessa*), *Nephrops*, cod, monkfish (*Lophius piscatorius*), lemon sole (*Microstomus kitt*), sole (*Solea solea*), turbot (*Psetta maxima*), and saithe, in that order, are the most important species. In the Skagerrak, *Nephrops*, plaice, cod, saithe, lemon sole, haddock, and monkfish are the most important species. In the Kattegat, *Nephrops*, sole, and plaice constitute the primary catch value. Several other species, such as witch (*Glyptocephalus cynoglossus*), hake (*Merluccius merluccius*), ling (*Molva molva*), halibut (*Hippoglossus hippoglossus*), and pollack (*Pollachius pollachius*), can also be important target or bycatch species in some fisheries. Several different fisheries are based on the above species, where one or two species are the primary targets and the other species contribute to the total catch value. The fisheries can vary from single-species directed to multispecies directed (including 10–15 commercial species), and the quantity and composition of the catch of these species can vary greatly with depth, fishing ground, and season.

2.3 Survival of fish escaping through codend meshes

Mesh size regulation is the most commonly used technical measure enforced by regulators for conservation of fish. An implicit assumption traditionally made in fish stock

assessment is that escapees survive the mesh penetration and are able to make a full recovery (Breen and Cook, 2002). Experiments have demonstrated that cod in particular (Suuronen et al., 1996; Jacobsen, 1994; Soldal et al., 1993), but also haddock and whiting (Soldal et al., 1993; Sangster et al., 1996; Soldal and Engås, 1997; Wileman et al., 1999; Breen et al., 2007), do in fact have a high survival rate after escaping a trawl by mesh penetration. Madsen et al. (2008) and Grimaldo et al. (2009) demonstrated that escapes take place not only during towing at the seabed but also during the short period during which the trawl is hauled back from the seabed and while the codend is at the surface. The survival of escapees during these stages of the haul back operation is likely to be reduced due to increased stress, especially for the physoclistous roundfish, due to decompression injuries, but also due to predation at the surface from seabirds. The high survival rates of juvenile fish escaping the trawl near the seabed argue for the development and use of selective fishing gear designs that allow the juveniles to escape and survive instead of being caught and subsequently discarded.

3. Size selectivity

3.1 Size selectivity and methods used to study size selectivity

Size selection of fish by a fishing gear is a process that causes the catch of the gear to have a size composition that differs from that of the population of fish that was present in the trawl's path during the fishing operation (Wileman et al., 1996). The selectivity of a fishing gear is a consequence of the selection process. Measuring size or mesh selectivity of a trawl is traditionally conducted considering only the codend because studies and underwater observations have shown that most escapement of fish occurs in that section of the gear (Beverton, 1963; Main and Sangster, 1981; 1991; Wileman et al., 1996; O'Neill et al., 2003). Experimental studies have, however, shown that substantial selection of *Nephrops* can occur in the main body of the trawl, and this also may be the case for other crustaceans (Hillis and Early, 1982; Wileman et al., 1996).

Wileman et al. (1996) recommended that selectivity experiments be conducted onboard commercial vessels. Thus, all the data herein are from sea trials conducted onboard commercial vessels fishing on commercial fishing grounds. A selectivity experiment includes the collection of length-frequency data for the population of fish available for capture and for the fish retained by the experimental fishing gear. Selectivity results are often presented in terms of two parameters: the 50% retention length (L50) and the selection range (SR). L50 is the fish length that corresponds to the 50% likelihood that the fish will be retained by the gear, and SR is the difference in the length between the 25% and 75% retention probabilities. Several methods can be used to

obtain data to calculate the selectivity of a given codend or gear design. For example, the covered codend method uses a small mesh cover attached over the codend; the cover retains fish and other aquatic organisms that escape through the codend meshes. It is, however, essential that the cover is attached in a way that does not affect the relative ability of fish of different sizes to escape from the codend (Wileman et al., 1996; Madsen and Holst, 2002). The covered codend method is the most suitable method for measuring the codend selectivity and should be used when possible (Herrmann et al., 2007b; Sistiaga et al., 2009). This method provides direct quantities of the escaping fish from the catch in the cover, whereas the paired and alternate methods only give estimates of the escapement from the codend.

A second and more diverse group of selectivity methods can be referred to as the *paired-gear* methods, which include the alternate haul, parallel haul (involving two vessels), twin trawl, and trouser trawl (Wileman et al., 1996). In these methods, two gears are towed alternately or alongside each other. One of the codends is made of small mesh netting to sample the population of fish that the trawls encounter, thus the length-frequency distributions of fish from the two codends allows the calculation of the selectivity parameters of the experimental codend. Therefore, the paired gear methods can determine both codend selectivity and whole gear selectivity (Wileman et al., 1996). However, recent studies have demonstrated that the paired-gear techniques may require a substantially greater number of trawl hauls than the covered codend method to obtain the same reliability of the selection parameters and that the estimation of these parameters in some cases can be biased (Herrmann et al., 2007b; Sistiaga et al., 2009). The catch-comparison method is similar to the paired-gear methods except that the population of fish entering the trawl is not collected with a small meshed codend. Using the catch comparison method, different gear modifications can be directly compared (e.g., the effect of inserting a SMP or an increased codend mesh size can be estimated, as in Paper 1). The parallel-haul technique often is used as a catch comparison technique, and two relatively similar vessels are used. Two completely different gear designs can be compared with this technique (e.g., Revill et al., 2006; Holst and Revill, 2009). The parallel-haul method is, however, likely to exhibit greater variance of the selection parameters because two trawls do not, in general, encounter exactly the same population despite their proximity (Wileman et al., 1996). An advantage of the catch comparison method is that fishing can be conducted under full commercial conditions, including commercial towing time and catch sizes, which often is difficult in covered codend experiments. As reported in Paper 4, the vertical separation of fish was studied by comparing two different vertical separator frames in a twin-trawl experiment.

3.2 Factors that affect size selection

Mesh size is a design feature that has one of the most significant effects on fish size selection (Reeves et al., 1992), but several other parameters also greatly influence size selection in the codend. Increase of the codend twine thickness can reduce the L50 (Lowry and Robertson, 1995; Wileman et al., 1996; Herrmann and O'Neill, 2006; Sala et al., 2007) and twine material stiffness can influence the mesh opening angles (Tokac et al., 2004). Vessel type (Tschernij and Holst, 1999) and sea state (O'Neill et al., 2003) can influence the selection process as well. Codend attachments (Kynoch et al., 2004) and restrictions (Lok et al., 1997; Herrmann et al., 2006), the length of extensions (Reeves et al., 1992), the codend circumference (Reeves et al., 1992; Galbraith et al., 1994; Broadhurst and Kennelly, 1996; O'Neill and Kynoch, 1996; Lok et al., 1997; Herrmann et al., 2007a; O'Neill and Herrmann, 2007; O'Neill et al., 2008), and catch weight (Campos et al., 2003; Herrmann, 2005) also have been reported to affect the size selection process in codends. Some of these mechanisms affect codend selectivity because they affect the shape of the codend and thereby the mesh opening angles (oa values) and shapes. The predicted effect of the codend shape and the meshes' oa value as a function of increased catch accumulation in the codend during the fishing process is illustrated in Fig. 4. Reducing the mesh size in the codend or the number of meshes in the codend circumference will result in more open meshes at lower catch weight whereas the opposite will delay this opening process until larger catch weights are obtained.

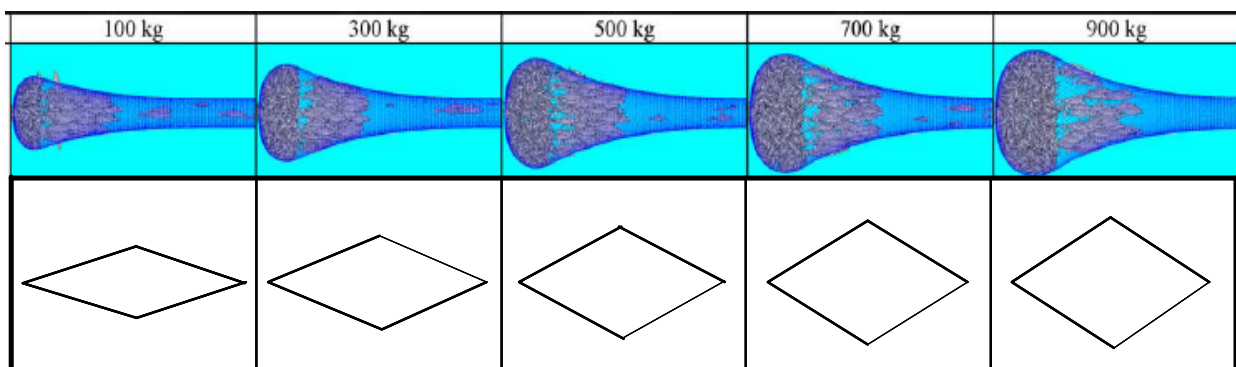


Fig. 4. Codend shape and mesh opening angle versus catch for a 100 mm diamond mesh codend with 100 meshes in the codend circumference (calculated with FEMNET data from Herrmann et al., 2006).

Changes in design parameters such as mesh size, number of meshes around the codend circumference, or twine diameter result in controlled variations in the selection process. In a codend designed with fewer meshes in the circumference, the maximum perimeter of the codend will be reached at a lower catch weight (Herrmann et al., 2007a). The meshes just in front of the catch accumulation will thereby obtain greater mesh opening angles (oa values) at lower catch weights earlier in the fishing process. The haul-to-haul variation that occurs despite these design parameters being kept constant is due to uncontrolled variables such as the randomness of fish

arrival in the codend and the total catch size (Herrmann and O'Neill, 2005), as well as vessel movements and weather conditions.

3.3 Size selective devices used to reduce the bycatch of cod

Glass (2000) stated that fish escapement from fishing gear is affected by either mechanical sorting mechanisms based on size or by utilizing species-specific behaviour patterns. The size selective devices described below utilize the behaviour patterns in a limited way. The effect of the size selective devices (e.g., the SMP) does, however, depend on fish behaviour because fish can actively try to penetrate and escape through the panel meshes, avoid them, or do nothing. Species-specific behaviour towards these size selective devices may therefore result in improved species selection.

The main legal measure for preventing catches of juveniles has been a minimum mesh size regulation. Clearly the minimum landing size (MLS) should in some way relate to the selectivity of the gear or vice versa. Fisheries managers often aim for a relationship in which the minimum mesh size in the codend will result in a 25% retention length (L₂₅) that corresponds to the MLS of the fish (Reeves et al., 1992). However, the possibilities for effective application of this relationship are limited in multispecies fisheries because different species grow to different sizes and mature at different sizes and therefore require different mesh sizes.

A number of adaptations to trawl designs exist that are aimed at improving the size selection of cod and other species in demersal trawls. In general, the methods and considerations are different in single-species cod fisheries like those in the Baltic and the Barents Sea compared to multispecies fisheries like those in the North Sea, where cod is caught along with numerous other species. In a single-species fishery, mesh type and mesh size and other design parameters can be adjusted in accordance with the morphology of the one target species. In contrast, in a multispecies fishery optimal size selectivity for one species may result in either discard of juvenile individuals or loss of individuals of marketable size of other species. For example, cod is one of the few large species caught in the mixed-species fisheries in the Kattegat-Skagerrak and the North Sea; regulating the mesh size and mesh type based on the morphology of cod in this multispecies fishery could result in loss of smaller species with a lower MLS or with the same MLS but a body shape that is different from that of cod.

One of the simplest and most used measures available to improve the size selection in the codend is to increase the mesh size. Results of such modifications indicate that a larger codend mesh size results in a larger L₅₀ (Halliday et al., 1999; He, 2007; Paper 1). In a *Nephrops* directed

multispecies fishery, a codend mesh size increase can dramatically change the species composition in the catch and can lead to an increased catch of cod above the MLS (Paper 1).

Throughout the world, SMPs have been used in codends to reduce unwanted bycatch of juvenile individuals of fusiform fishes (e.g., Ridderstad, 1915; Briggs, 1992; Broadhurst and Kennelly, 1995; Armstrong et al., 1998; Madsen et al., 1998; Graham and Kynoch, 2001; Madsen et al., 2002; Graham et al., 2003; Broadhurst et al., 2006; Revill et al., 2007). In contrast to the case for species such as whiting and haddock (e.g., Armstrong et al., 1998; Graham and Kynoch, 2001; Graham et al., 2003; Revill et al., 2007), only sparse data are available about the ability of a SMP to reduce the catch of juvenile cod (Madsen et al., 1999). In terms of selection of roundfish, some researchers have reported that the efficiency of a SMP increases when it is closer to the cod line (Graham and Kynoch, 2001; Graham et al., 2003), but others have reported conflicting or contradictory conclusions (Armstrong et al., 1998; O'Neill et al., 2006). Different trawl designs and different positions of the SMP may provide an explanation for these conflicting results (Paper 1).

Experiments with diamond mesh panels with a considerably larger mesh size than that used in the rest of the trawl (called large-mesh panels) also have been studied to reduce the catch of cod (Madsen et al., 2006). Large mesh top panels have especially been tested in the beam trawl fisheries. Van Marlen (2003) reported a 30–40% reduction of the catch of cod and whiting using this technique in the North Sea beam trawl fishery. However, very few cod were caught in the experiment, which may have affected the precision of the results. The use of large mesh bottom panels also has been tried in an effort to reduce the flatfish bycatch in the small-meshed trawl fishery for silver hake (*Merluccius bilinearis*) (Milliken and DeAlteris, 2004).

Codends made entirely of square meshes have been tested extensively in various fisheries (e.g., Robertson and Stewart, 1988; Walsh et al., 1992; Stergiou et al., 1997; Halliday et al., 1999; He, 2007; Sala et al., 2008; Valentinsson and Ulmestrand, 2008; Broadhurst and Millar, 2009). In general, the use of a square mesh codend increases the L50 and reduces the SR for roundfish compared to a diamond mesh codend with same mesh size. Halliday et al. (1999) reported a 10% increase in the L50 and a one-third narrower SR for cod when a square mesh codend was used. In contrast to the case of roundfish, the very different morphology of flatfishes seems to prevent them from escaping through square meshes compared to diamond meshes (Walsh et al., 1992; He, 2007). In some cases, the catch composition in the codend has been reported to influence the codend mesh selection (Wileman et al., 1996). The presence of one species may prevent the escape of others; flatfish, for example, will block meshes in the codend, preventing under-sized roundfish from escaping (Glass, 2000).

Experimental work (Dahm, 2004) has indicated that turning the diamond-mesh netting by 90° (T90) may increase the L50 for a codend compared to a similar codend with a normal netting orientation. With the normal netting orientation (T0), twine stiffness tends to keep the meshes closed. Turning the netting by 90° reverses this mechanism and twine stiffness tends to keep the meshes from closing, which facilitates the escapement of juvenile roundfish through the meshes (Herrmann et al., 2007a). The netting knot size, which is defined by the knot type and twine characteristics, may also affect the benefit of turning the netting by 90°. In 2006, the use of T90 was introduced into the legislation for the Baltic Sea cod fishery as a legal alternative to the BACOMA codend. The BACOMA codend is a diamond mesh codend with a 110 mm SMP placed in the upper panel of the codend stretching forward 3.5 m from a position four meshes from the codline. Little experimental work has been published on the subject, but theoretical work (Herrmann et al., 2007a) indicates that compared to a normal diamond mesh codend with 100 meshes in the circumference, the Baltic T90 codend with 50 meshes in the circumference will increase the L50 with 12 cm. About 70% of this increase, however, stems from the reduction in the number of meshes in the circumference (Herrmann et al., 2007a).

Use of a selection grid is an alternative to using different mesh sizes or mesh types. Rigid grids were first introduced into the shrimp trawl fisheries to reduce the bycatch of turtles (Watson and McVea, 1977) and juvenile fish (Isaksen et al., 1992). A large number of selective grids have been tested in a variety of fisheries (Anon., 1998). In the North Sea and Skagerrak areas, grids are used on a voluntary basis in the Danish shrimp (*Pandalus borealis*) fishery. In the Kattegat and Skagerrak fisheries directed towards *Nephrops*, the Swedish *Nephrops* grid in combination with a square mesh codend (Valentinsson and Ulmestrand, 2008) can be used as a legal alternative to a 90 mm codend with a 120 mm square mesh panel inserted in the upper panel. Recent Danish experiments with a *Nephrops* grid that was modified compared to the Swedish *Nephrops* grid (Valentinsson and Ulmestrand, 2008) with the aim of reducing the loss of *Nephrops* resulted in a 17% loss of marketable *Nephrops* (Frandsen et al., in press). The *Nephrops* grid is very efficient in minimizing the catch of fish, but in the mixed-species fisheries this can mean losses of catch value of around 50–60% (Paper 1). Despite the fact that no restrictions on fishing effort exist when using the grid, the grid is not used in Danish waters today. In several studies, the performance of the grids was analysed and compared with that of other selective systems (Graham et al., 2004a; Kvamme and Isaksen, 2004; Jørgensen et al., 2006). Experiments in the Barents Sea cod fishery showed no evidence that the combined grid and codend selection had a sharper size selection (smaller SR) than that of codend meshes alone (Jørgensen et al., 2006). In terms of the L50, mesh selectivity is more sensitive to changes in stomach fullness and conditions than is grid selectivity. On the other hand,

the L50 of the grid was found to be sensitive to differences in catch rates while the mesh selectivity was not (Jørgensen et al., 2006).

Increasing the MLS for cod will not necessarily reduce the fishing mortality of cod. The MLS must agree with the actual size selection that occurs in the gear so that caught cod can be legally landed instead of being discarded dead. High-grading has been reported, which means that individuals above the legal landing size are discarded due to large difference in price. Large individuals often are worth 3–4 times more than individuals just above the MLS. High-grading typically occurs when quotas are significantly lower than the catch capacity of a vessel or a fleet.

3.4 Size selection: Results and their relevance

Graham et al. (2003) examined the size selective effect of inserting a 90 mm SMP in three different positions into a trawl in the North Sea fishery for haddock and whiting. The L50 was found to increase for both species when the SMP was moved aft towards the codline. In the highly mixed *Nephrops* directed fisheries in the Kattegat-Skagerrak, such thorough experiments had not been conducted despite extensive use of SMPs in this fishery. Thus, such experiments were undertaken in Paper 1: In that study, the effects of introducing a SMP, the position of the SMP, the SMP mesh size, and its use as an alternative to increasing the codend mesh size were examined in catch comparison experiments including nine different species under strict commercial conditions. A simple economic model based on average prices for the different size categories for each species of fish and *Nephrops* was used to examine the direct effects on the income of the fisherman using the device. A 120 mm SMP positioned 6–9 m from the codline was introduced in Kattegat-Skagerrak fishery based on this experiment (EC Reg. No. 15238/04).

In catch comparison experiments like those conducted in Paper 1, two different gear designs and their selective performance are compared. However, we do not know the selective potential of a given SMP because we do not know which size fish can physically escape through the SMP. This means that we do not know if 20% or 80% of the fish are able to escape through the panel and whether or not they actually do so. To be able to estimate the absolute efficiency of a SMP we need to know its selective potential. This baseline can be obtained by testing a full square mesh codend with the covered codend method for each SMP and codend mesh size combination. Alternatively, we can find the morphological parameters that determine the ability of a given species to penetrate different meshes and establish a penetration model for the species. Paper 2 describes the use of a novel methodology (including the tools and software) developed and used to measure the morphological parameters that determine the ability of cod to penetrate different mesh types, sizes, and openings. This methodology, called FISHSELECT, involves a series of steps, and

the final output is used to predict the selective characteristic of different netting types and combinations; it also can be used to explore the mechanisms that cause variations in the selection process found in experimental data.

Paper 2 includes analyses of results from morphology-based simulations of four different types of meshes (diamond, square, rectangular, and hexagonal). The data show that use of the commonly used diamond shaped meshes results in substantially lower predicted L50 estimates for cod than use of the hexagonal meshes when both types of meshes have optimal opening angles (oa values) for cod. For each mesh type, a design guide was developed; it shows the basic selective properties, in terms of L50, for various mesh sizes as a function of oa (Fig. 5). The general tendency for the management of the fisheries in the Kattegat-Skagerrak and the North Sea areas over the two decades has been to increase the codend mesh size, which corresponds to moving along the x-axis in Figure 5. The low slopes of the iso-L50 lines for the small oa values in the lower part of the figure (corresponding to small catches) show that a large increase of the mesh size is required to increase the L50 for small catches. However, because oa increases gradually (that is, moving in the y-direction of the figure) during catch build-up, it also means that the SR will become rather large, as the minimum size of fishes retained by the gear will increase gradually during the fishing process.

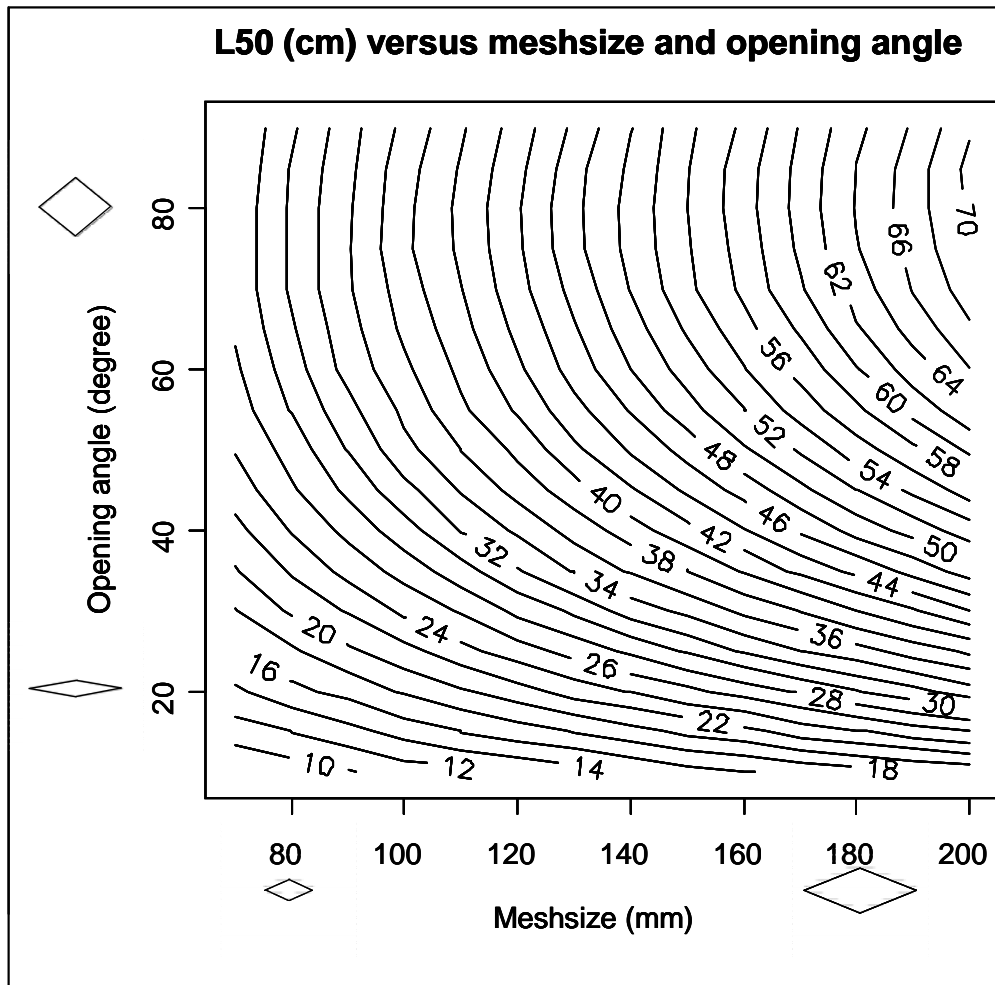


Fig. 5. Diamond mesh design guide showing iso-L50 curves as a function of mesh size and mesh opening (oa value). The right side of the figure corresponds to a square mesh (oa = 90°).

These results indicate that the major source of variation in the selection process is caused by the varying oa values that occur during the catch build-up process. This is good news, because the major source of variation originates from variability that we can control. Thus, if there is sufficient catch for the codend to reach its maximum perimeter, the ao value will be more stable in the selective area in front of the catch build-up. However, all tows go through a phase with large variation, and fisheries with relatively low catches in relation to the codend perimeter will exhibit large within-haul variation. Considerably higher L50 values and lower SR values could be obtained if high oa values could be maintained throughout the fishing process. In this case, the within-haul variation would be reduced to a level that is caused only by the morphological variations among the caught fish, which is a parameter out of our control. The contribution of the morphological variations to the SR value obtained during sea trials is predicted to be about 14–18% for cod (Paper 2).

Morphologically based simulations of selective properties of different netting designs can not substitute sea trials because gear selectivity is also affected by parameters such as fish behaviour, vessel size, and sea state (Wileman et al., 1996). Simulations can, however, be a useful tool to explore and understand the mechanisms acting under the selection process. Gear designs can be optimised theoretically with relatively low cost, after which only the most promising designs are subjected to expensive and time-consuming sea trials. A further advantage of simulation methodology is that the limits of what can be obtained by size selection in a given fishery for a given species can be quantified. This will allow managers and gear designers to predict whether or not size selection can potentially solve a given problem in a given fishery or if other management tools are required.

There is an increasing, both political and public involvement in requiring the fisheries to become more sustainable. Requests for new and more selective fishing gears to address bycatch or discard problems in specific fisheries now are more often put forward. The FISHSELECT methodology provides a predictive platform for a quick theoretical optimisation of a newly developed selective or already existing gear designs and the consequences in terms of discard and lost marketable catch. If morphological data were collected and penetration models were established for all of the important species in the Kattegat-Skagerrak and North Sea multispecies fisheries, detailed quantitative multispecies predictions could be made with different population scenarios.

A new rights-based regulation (FKA – Vessel Quota Share) was put in force in Denmark from 1 January 2007. With the new system, individual vessels are allocated a yearly share of the Danish quota, which can be taken at any time of the year. There is also a possibility to trade it, exchange it, or pool it with other fishers. The old regulation had a system with 14-day quotas, which continuously adjusted to the remaining national quota. The new system gives the industry a possibility for better planning and is expected to lead to a more efficient fishery with less discards (ICES 2008). Currently, no regulations exist, that address the quota rights that a vessel has to possess to participate in a given fishery. The discard can be reduced if the fishing rights of a single vessel better reflect the population structure the vessel is expected to meet on the fishing ground and the gear it uses. Due to individual transferable quotas (ITQ), the fishing rights of a single vessel can be designed by the single vessel owner via the quota trade. A qualified guess on such *optimal* quota rights in relation to population expectations could be aided if morphological data were collected for all of the involved fish species. This could also help identify discard-intensive population combinations versus quota rights.

4. Behaviour-based selectivity

4.1 Fish behaviour in relation to trawls

The evolution of trawl design has been driven largely by fishermen's understanding of fish behaviour. However, during the last three decades fish behaviour in relation to fishing gear has been studied intensively because a more systematic understanding of fish behaviour has become increasingly important for fishing gear technologists trying to develop more species-selective trawls to minimize bycatch and subsequent discarding. Furthermore, the growing tendency towards fishery-independent stock-assessment methods requires that the different stages of the capturing process can be quantified because data about survey trawl catches provide an important part of the basis for calculating population indices (Graham et al., 2004b).

Trawls capture fish by taking advantage of their avoidance or anti-predator behaviour. Fish with different anti-predator strategies are likely to respond differently to approaching trawl gear. Main and Sangster (1986) observed that different species react in predictable and different ways as they tire in towed fishing gear. For example, roundfish respond to an approaching trawl at a greater distance and have stronger burst and swimming capabilities compared to flatfish (Ryer, 2004). Behavioural studies in the trawl mouth have shown that haddock and, to a lesser extent whiting and saithe, rise up above the ground gear as they tire, whereas flatfish, cod, and *Nephrops* enter the trawl close to the sea bed (e.g., Main and Sangster, 1981, 1982; 1985a; 1985b; Galbraith and Main, 1989; Thomsen, 1993; Ingolfsson and Jørgensen, 2006). The tendency to exhibit varying degrees of rising in the trawl has led to the development of multi-level trawls, with horizontal separators and multiple codends, which allow partial segregation of the catch by species (Main and Sangster, 1982; 1985a; Cotter et al., 1997; Engås et al., 1998; Ferro et al., 2007). The strong affinity of cod for the seabed at the trawl mouth was illustrated in a Barents Sea experiment in which one third of the cod were observed to escape between or under a commercial rockhopper gear (Ingolfsson and Jørgensen, 2006). Similar affinity for the seabed is found for cod in paper 3. Attempts to separate cod from other catch components into the upper codend also have been made. Hillis (1989) obtained limited success using guiding ropes that were stretched diagonally from the separator panel to the trawls belly sheet. Sangster et al. (2003) used a similar method, and most cod were separated from *Nephrops* and flatfish. Adjusting the length of the guiding ropes, however, proved difficult and only a low number of cod was encountered during the experiment.

Limited observations of cod in trawl nets indicate that they drift slowly back along the codend extension, staying stationary in the net for long periods of time (Briggs, 1992; Briggs and Robertson, 1993). Based on underwater observations, Thomsen (1993) reported that once inside the

trawl, cod tended to rise, as did other gadoids such as haddock and whiting, although their rate of ascent was far slower and further aft in the trawl. Thomsen (1993) further indicated that the difference between cod and flatfish became more distinct further aft in the trawl. These results are confirmed and quantified in paper 4. Thomsen (1993) did not distinguish between the different species of flatfish in this study. Several observations of flatfish behaviour have been made with camera systems inside trawls (Main and Sangster 1982; Galbraith and Main, 1989; Thomsen, 1993; Bublitz, 1996; Ryer, 2008). In the Danish fisheries, different species of flatfish, such as plaice, lemon sole, turbot, sole, and witch, are economically important. In general, it has been difficult to distinguish among the different species of flatfish in optical observation studies. Potential species-specific differences in behaviour among these species are therefore difficult to uncover using optical methods.

The behaviour of flatfish during herding, net entry, and passage through trawls differs substantially from that of many roundfish (Main and Sangster, 1981; Bublitz, 1996; Ryer, 2008). These differences result from the unique morphology of flatfish and the constraints that this morphology places on their natural predator avoidance and evasion tactics (Ryer, 2008). Flatfish swim in a burst pattern, which suggest that they would quickly become exhausted and enter the net, contrary to roundfish, which exhibit a more continuous swimming behaviour when herded by fishing gear. As a result, flatfish seem to respond to the groundgear at shorter distances, closer to the seabed, and for shorter periods of time (Ryer, 2008).

In summary, extensive research over the last four decade has demonstrated that selection is not achieved solely by mechanical means, and laboratory studies (e.g., Baxter and Perrish, 1959; 1966; Cui et al., 1991; Glass et al., 1993; 1995) and observations made at sea have shown that behavioural reactions play an important role in the capture process (e.g., Wardle, 1983, 1987, 1989, 1993; Glass and Wardle, 1989; Walsh and Hickey, 1993; Bublitz, 1996; Ryer, 2008). Extensive knowledge of fish behaviour in relation to fishing gear has been gathered since the 1960s, especially for species such as haddock and whiting at certain sections of the trawl. More detailed information about the economically important species for the Danish fleet and the spatial route of these species through the trawl cavity are not so clear. However, such information could elucidate the potential for species separation in demersal trawls based on behaviour.

Where size selection of fish primary occurs in the codend, do fish behaviour in relation to the fishing gear occurs throughout the capturing process. Changes made to the trawl rig, from the trawl doors to the codline, may therefore affect the species selectivity of the gear. Gear modification can be made to avoid the initial capture of unwanted species (species selection) rather than to improve their chances of escape from the trawl (primarily size selection).

4.2 Study of fish behaviour in trawls

Fish behaviour studies can vary from simple observations about spatial preferences of a single species at a specific point in the trawl to complex multispecies interactions between fish and fishing gear throughout the catching process. The technologies used to study fish behaviour vary accordingly and range from simple camera systems to advanced acoustic systems or a combination of both. Recent advances made in optical, acoustic, and data-processing technologies to study fish behaviour are reviewed in Graham et al. (2004b).

The use of direct camera observations of fish behaviour in relation to towed gear was pioneered and extensively used by scientists at the Marine Laboratory at Aberdeen (see e.g., Main and Sangster, 1981, 1983, 1991). The development of these techniques and the main conclusions of the work are outlined by Wardle (1983, 1987, 1989, and 1993). Today, fish behaviour in relation to fishing gear is studied around the world. Camera observation techniques have provided unique inside information about how different species of fish react to the fishing gear through different stages of the capturing process. Although the quality of underwater cameras has improved greatly since the 1960s recording fish behaviour can fail due to turbid water and the rapid reduction in natural light at depth. High-resolution scanning sonar systems provide direct observations at greater depth (Engås and Ona, 1990; Graham et al., 2004a, Ferro et al., 2007), but the recorded fish echoes still must be identified to species. This can be accomplished by using flash photography, but this method requires relatively high densities of fish to produce a sufficient number of images containing the target species and may itself affect fish behaviour.

Substantial species-specific differences exist, both in the herding process in front of the ground gear and in how fish react when they pass the ground gear and enter the netting part of the trawl. Direct video observations have shown that flatfish typically are herded into the trawl path after direct or near contact with the doors, the sweeps, or the sand cloud created by the trawl (Main and Sangster, 1981) and that the majority of flatfish do not actively swim upwards but rather utilize a rapid escape manoeuvre to avoid the groundgear (Bublitz, 1996). Hall et al. (1986) and Wardle (1987) reported that the roundfish reaction distance is limited by the visual field, the visual range, and their swimming ability. Experimental results further suggested that in the absence of vision, fish only react to a moving net by a startle reaction when struck by the net and that the other senses do not take over to guide and herd them away from the fast approaching net (Glass and Wardle, 1989). Bublitz (1996) and Walsh and Hickey (1993) reported that flatfish initially react to the gear well within their visual limits, suggesting vision may not be the critical factor in determining flatfish reaction distance.

The different methods used to study fish behaviour have covered a relatively limited field of view or observation scene, partly due to the limitations of the observation tools, but especially due to the rapid reduction of natural light at depth. This problem in combination with the speed at which the fish pass the observation scene can make it difficult to identify them to species. In addition to optical and acoustic methods, horizontally divided separator trawls have provided information about fish behaviour in terms of vertical preferences (e.g., Main and Sangster, 1982). An advantage of this indirect method is that it can be successfully used independent of depth, water turbidity, and light conditions, all of which affect traditional camera techniques. However, fish behaviour cannot be observed directly with such a technique. Even so, based on separate catch proportions obtained with a separator trawl, a description of the behavioural process can be made. This is an example of how use of a structural model in combination with biological parameters obtained experimentally from catch data can provide quantitative information about the behavioural processes that occur in the trawl during the catching process. Another advantage of the separator trawl method is that all fish caught can be identified to species and measured, in contrast to optical studies in which low identification successes are reported (Krag et al., in press). A disadvantage may be that the separator panels or similar structures used to separate the upper and lower parts of the trawl may themselves affect fish behaviour.

4.3 Factors affecting fish behaviour in relation to fishing gear

Separating different fish species from each other requires that at some stage of the capturing process they behave differently and that this behaviour is relatively constant under the conditions for which a particular separation device is designed. Fish seem to base their behaviour reaction to fishing gear primarily on vision. The behaviour reaction of fish can be explained by visual response to the moving background of the towed net (Wardle, 1983; 1986a; Glass and Wardle, 1989). Visual acuity of a fish depends on the available light levels and the turbidity of the water, thus changes in those abiotic parameters affect the behavioural response of fish to the fishing gear. Field and laboratory studies suggest that trawl bycatch reduction strategies that rely on the premise that undersized or non-target fish use vision to guide them out of the net may be less effective at night or at depths where ambient light levels are below critical levels (Glass and Wardle, 1989; Wardle, 1993; Ryer and Olla, 2000; Ryer, 2008). Observations made inside a trawl at very low light levels suggest that fish show none of the patterns of avoidance behaviour that are typical in daylight (Wardle, 1986b). Glass and Wardle (1995) experimentally demonstrated that in the absence of vision, fish are unable to react in an orderly manner to an approaching net. Most trawl gears appear to rely on the visual stimulus of the sweeps and sand clouds to herd the fish

inwards to the high contrast headline. At extremely low light levels, Glass and Wardle (1995) reported that this herding ability is lost, resulting in a greatly reduced area swept by the trawl. This tells us that none of the other senses is used by the fish to orientate themselves or react to fishing gears within the short time period available at commercial towing speeds.

The swimming capacity of fish and hence their susceptibility to capture is a function of temperature, state of exhaustion, and the speed of the gear through the water. Selection may therefore vary with season, time of day, and fish condition. Changes in tides, currents, light levels, temperature, or other diurnal or periodical factors may cause changes in the behaviour of fish, and hence in the population structure and/or the selection process (Wileman et al., 1996).

4.4 Trawl designs using behavioural differences to reduce the catch of cod

In this review, the discussion of size and species selection has been divided into separate chapters. The difference between size and species selection, however, is not so clear. One could argue that a SMP is a size-selective device based on escapement restricted by the mesh size through the panel. The position at which the panel is installed in the trawl, however, results in more efficient escapement of some species than others. Similar examples can be found for other selective devices (e.g., grids or large mesh panels). Furthermore, the population structure in which fishing is conducted can affect whether a selective device improves the size or species selectivity.

Several experiments using horizontally separated trawls have shown a clear separation between haddock, saithe, and whiting and species such as *Nephrops*, flatfish, monkfish, and cod (e.g., Main and Sangster, 1985a; Galbraith and Main, 1989; Engås et al., 1998; Ferro et al., 2007: Paper 3). The trials have demonstrated effective collection of the majority of haddock, whiting, and saithe in a top compartment. However, further development is needed so that after separation those species entering the lower compartment (principally cod, monkfish, and flatfish) can be confronted with a size selective device, such as a grid, with a bar spacing chosen to release cod of suitable size (Ferro et al., 2007). He et al. (2008) used horizontal ropes between the selvages in combination with a black tunnel to separate haddock from yellowtail flounder. Most haddock and 60% of the cod were caught in the upper compartment, which is in contrast to results from the netting separator panel studies.

Raised foot rope trawls have been developed and tested in the northwest Atlantic. In this type of gear, the trawl is raised above the seabed to allow cod and other groundfish species to escape beneath the trawl. The traditional ground gear of the trawl is replaced with drop chains hanging from the fishing line (McKiernan et al., 1998). Milliken and DeAlteris (2004) reported that the raised foot rope device performed well in field research, but in practice the performance of the

sweep is highly variable and determined by individual adjustments to the gear. Based on reported behavioural responses of fish to twine colour, Milliken and DeAlteris, (2004) suggested the use of an orange-coloured, large-mesh escape panel in the lower belly section to reduce the catch of flatfish while not affecting the catch of silver hake (Wardle et al. 1991; Wardle 1993; Glass and Wardle 1995).

Beutel et al. (2008) investigated the performance of a large-mesh faced (large-mesh panels in the upper and lower wings, side panels, and first bottom belly) bottom trawl designed to capture haddock while reducing the bycatch of cod and other species in the northwest Atlantic. The catch of cod and flatfish was significantly ($P < 0.05$) reduced when this design was used. A similar design was also tested in the North Sea haddock fishery, and the catch of cod was reduced with 89% (Holst and Revill, 2009).

The majority of trawls are designed to be rigged with the headline located more forward than the foot rope and thus do not permit fish to escape upwards (Revill et al., 2006). Thomsen (1993) developed a cut-away or topless design to target flatfish in a coastal mixed-species fishery targeting flatfish in the Faroe Islands. This significantly reduced the catch rates of haddock while maintaining the catches of flatfish. A similar design was tested in the North Sea fishery directed towards *Nephrops* (Revill et al., 2006); in this case no significant difference was detected for cod compared to a standard trawl. Pol et al. (2003) found a significant reduction of cod in the northwest Atlantic when a topless design was used in a coastal fishery targeting flatfish. Chosid et al. (2008) also had success in reducing the catch of cod in a high-seas fishery for flatfish on the Georges Bank. However, they also reported large losses of the target species, yellowtail flounder (*Limanda ferruginea*).

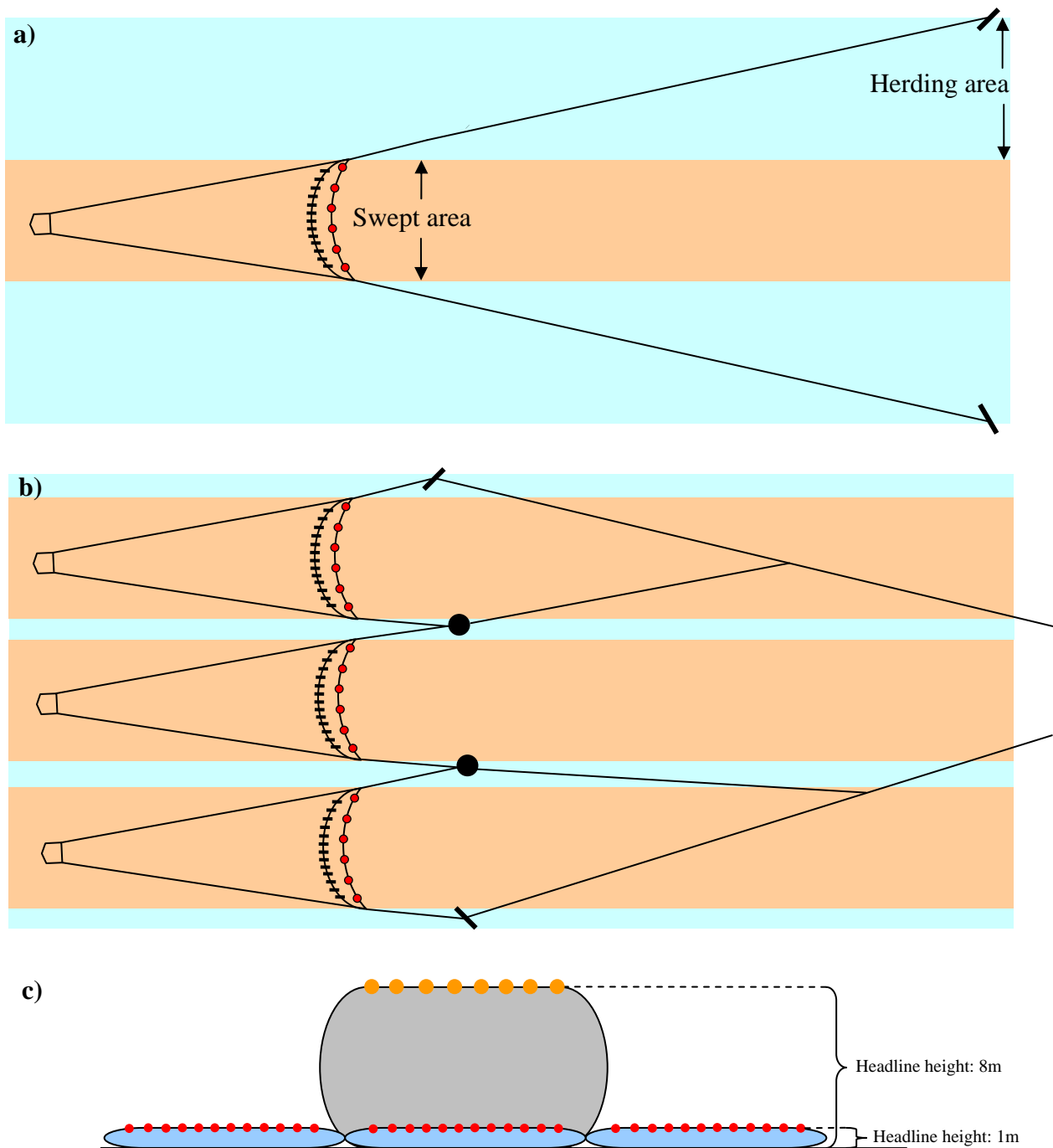


Fig. 6. Examples of species specific trawl designs. See the text for explanation.

Several studies have reported that the use of very long sweeps on bottom trawls enhanced the catch of some species of fish (e.g., Engås and Godø, 1989; Andrew et al., 1991). The use of long sweeps did not, however, increase the catch of slow-moving benthic species such as *Nephrops* and prawns (Main and Sangster, 1985b; Newland and Chapman, 1989; Andrew et al., 1991). Newland and Chapman (1989) reported that 50% of the *Nephrops* did not react to the trawl until touched by it. These observations indicate that catch of a large number of fish species such as

cod can be avoided by minimizing the length of the sweeps of the trawl and that this change should not affect the catch of *Nephrops* very much. The ratio between *Nephrops* and cod in the catch can therefore be adjusted by altering the length of the sweeps. Examples of species directed trawl designs are shown in Fig. 6. A trawl with relative long sweeps for catching fish such as cod is shown in Fig. 6a. The area swept by the netting part of the trawl is in this case small compared to the area between the otter boards which is swept by the sweeps (herding area). In Fig. 6b a more specialized trawl design for catching *Nephrops* in the triple-trawl rig with very short sweeps is shown. The vertical dimensions of the trawl can also vary considerable. In Fig. 6c the mouth openings of a whitefish trawl, like the gear used in Paper 3, is compared to those of the *Nephrops* triple-trawl rig shown in Fig. 6b. Species directed trawl designs can maximize the catch of the target species and minimize the catch of unwanted bycatch and thereby the need for further species selection within the trawls cavity which can result in loss of marketable species and sizes.

4.5 Species selection: Results and their relevance

The majority of the commercially important species in the Danish mixed-species fisheries enters the trawl close to the seabed along with cod. Thus, at the trawl mouth behavioural differences are not present to separate cod from the remaining major commercial species. Haddock, saithe and the economical less important whiting is an exception, in that they rises above the seabed when tired and falls back in the trawl (Paper 3). The critical conditions of the North Sea cod stocks have resulted in restrictions on not only cod but also on haddock and other species that are caught together with cod. Effort regulations and closed areas impact the fishery of all species, not just cod, so an alternative to non-specific measures is to develop a species-selective haddock trawl fishery that could allow full exploitation of the haddock stock independently of the stock status of other species.

Paper 3 describes the development and testing of a novel behaviour-based selective haddock trawl; its fishing line is raised about 60 cm above the seabed to allow cod of all sizes along with other groundfish to escape the trawl. The selective haddock trawl retained haddock efficiently and reduced the catch of cod substantially, with an 87% reduction at night and 44% during the day. In addition to the day-night dependency, a relatively strong length dependency of the separation success for both cod and haddock was observed. This emphasises the importance of testing behavioural-based gear designs both during the day and at night because the ability of fish to orientate in relation to a trawl can vary substantially between day and night. The advantage of the current design is that it aims to target only haddock and a few other species that raise when they

enter the trawl mouth; therefore, no subsequent selection between cod and other groundfish is required. The design is therefore simple and cost-neutral compared to a standard haddock trawl.

During tests the catch was collected in separate bags placed beside each other beneath the main codend. The majority of the fish that passed beneath the raised fishing line was caught in the centre collecting bag, which is consistent with results presented in Walsh (1991) and Ingolfsson and Jørgensen (2006). This indicates that the ratio of herding species (fish) and non-herding species (e.g., *Nephrops*) is quite different in the centre section of the groundgear compared to the population further forward in the trawl path. Providing this section with an escape possibility for fish could in theory select out fish with only a minor loss of non herding species like *Nephrops*. Species selective devices in the trawl mouth area do not necessarily have to cover the entire trawl mouth area but could be concentrated in the centre section of the ground gear.

Due the relatively large size of cod and their morphological resemblance to other roundfish, it is difficult to minimize the catch of cod by size selection without losing a large part of the marketable catch of other species. Haddock, saithe, and whiting can be separated from the majority of cod at the trawl mouth with the selective haddock trawl (Paper 3). However, this was not possible with economically more important species like *Nephrops*, flatfish, and monkfish.

Paper 4 describes a study in which the aft end of the trawl was divided into three vertically stacked compartments to investigate the vertical distribution of the commercially important species further aft in the trawl with the aim of separating cod from the other major catch components. Cod were observed to rise further aft in the trawl, but the separation of species was, in general, not as consistent in the aft end as it has been reported to be in the trawl mouth area. The vertical separation of cod was density dependent, indicating that a relatively large variation in the separation success can be expected with varying fish densities. As mentioned above, a major advantage of an observation technique such as the separator frame is that its successful use is independent of depth, water turbidity, and light conditions, all of which affect traditional camera techniques. Another advantage is that all fish caught can be identified and measured and flatfish can be identified to species, which has previously been difficult with the camera method (Thomsen, 1993; Bublitz, 1996). Physical sampling structures such as the separator frame (Paper 4) and separator trawls can, however, potentially affect the fish behaviour that they are designed to study (Krag et al., in press).

The results reported in Paper 4 demonstrate that a relatively large proportion of fish usually can be elevated in the trawl cavity with a simple stimulus. This observation could be utilized to separate fish from *Nephrops*. Simple stimulus or raising bars may also be used to improve the contact probability between fish and selective devices such as SMPs.

5. Final remarks and future work

Specific improvements in both size and species selection of cod have been demonstrated experimentally in the *Nephrops* directed fishery and for the haddock fishery (Paper 1 and 3). Both the position and mesh size of the SMP are key parameters determining the panel's ability to reduce the catch of juvenile cod and other fish in a trawl (Paper 1). To optimise the trade-off between discard reduction and loss of marketable catch, selective solutions must be specialized to specific fisheries. In general, the simpler a fishery is in terms of number of species, the more specialized and species-specific solutions can be obtained. It is possible to reduce the catch of cod at different stages of the capturing process (Paper 1 and 3). However, it is unlikely that trawls can be designed to completely avoid cod or select all cod out without large losses of marketable species and sizes.

The FISHSELECT methodology (Paper 2) opens new possibilities to studying size selection in a systematic way based on the morphology of fish and the shape of the mesh the fish experiences during fishing. Prior to this study, the effect of fish morphology relative to mesh penetration had not been quantified and parameterised systematically, which made a systematic search for optimal mesh types, sizes, and openings difficult. The basic selective conditions of different mesh types, mesh sizes, and mesh openings now has been found, and design guides were made for cod without having to conduct a large number of expensive and time-consuming sea trials. The methodology-based predictions can also aid the interpretation of experimental data and can be used to explore the selection process and its sources of variation. It was demonstrated that the catch size-dependent variation in the mesh oa values caused both the within-haul and between-haul variations in the selection parameters for cod, as reported from experimental studies. Methods or mesh types that can maintain a high oa value throughout the fishing process will improve the L50 and make the selection sharper by reducing the SR value. The hexagonal mesh was shown to be superior to the commonly used diamond mesh for cod because of a higher resemblance to the cross-sectional shape of cod. Such findings could, via simple means, improve the size selection of trawls for cod in the mono-species cod fishery in the Baltic Sea, if the Baltic cod have a similar morphology to the Skagerrak cod measured in Paper 2.

In this thesis, selective predictions are presented for cod for four different mesh types and a wide range of mesh sizes and oa values. To be able to make selective predictions for the Kattegat-Skagerrak and North Sea multispecies fisheries, the methodology has to include all of the species relevant for these fisheries. This work is in progress and the relevant morphological data have been collected for plaice, sole, lemon sole, turbot, haddock, and *Nephrops*, which all are of

major economic importance in the Danish demersal fisheries. The data for this group of species will allow quantitative multispecies predictions of both discard and catch losses in highly mixed-species populations of fish and crustaceans. Furthermore, they will allow the consequences, in terms of discard and catch loss with different quota combinations for vessels fishing on different populations of fish and crustaceans, to be estimated. Relationships between gear designs and fish population structures, which can potentially result in high discard rates, can also be identified. Managers will thus be able to explore a large number of different exploitation strategies without conducting as many expensive sea trials as before.

The methodology can predict the selectivity obtained by a given mesh shape, but it cannot estimate the shapes the meshes will obtain in different gear designs during the fishing process. However, finite-element-based estimation methods, such as FEMNET described by Priour (2001), can provide such shape estimations. If we know which mesh size and mesh shape a fish of a given length is capable of escaping through and the mesh openings and shapes present in a particular trawl design during a given fishing process, and if we use a covered-gear technique (covering the codend or using a SMP) during sea trials, then we can determine if the fish made use of the available escape possibilities. In this way, information about fish behaviour inside the trawl cavity can be estimated independently of available light and other physical and methodological difficulties that often reduce the success of direct observations of fish behaviour. The effects of the interaction of different species with different selective devices (e.g., SMPs, large mesh panels, or grids) can also be estimated with this method. The technique can be used to optimize the position of e.g. SMPs in different trawl designs.

Morphology-based theoretical optimisation is the first step in the design of a more selective gear type for a specific fishery. The second step is to build a full-scale model and test it under commercial conditions at sea to determine the predictive power of the methodology under these conditions. The second step has yet to occur. A comparison of sea trial results with theoretical results obtained with FISHSELECT has, however, been used to validate the methodology (Paper 2).

The technical legislation that specifies the gear designs that can be legally used in different fisheries is only one of the tools that managers can apply to regulate the fishing mortality of cod and other species in the ocean. Other tools include quotas, effort restrictions, closed areas, or a combination of these. The choice of management tool can have quite different effects on the ability of the industry to conduct an economically feasible fishery. For managers to be able to decide which tool to apply, they need to know what can be accomplished, in terms of both size and species selection, with the technical measures in a given fishery and at what cost (e.g., loss of catch of other relevant species). Including all relevant species in the structural-model-based simulation in

FISHSELECT will make it a predictive platform that can provide the theoretical limitations for size selection in various different scenarios. A simple economic model, similar to the one used in Paper 1, could be included to allow selective predictions and provide estimates of direct consequences for the industry. Currently, these questions cannot be answered in detail for most commercial species. However, there is a good understanding of fish behaviour and the potential for species separation in the trawl mouth for most of the relevant species in the Kattegat-Skagerrak and North Sea. Species separation further aft in the trawl, including the potential for altering fish behaviour with simple stimulation, has not been studied in detail for all of the relevant species.

Due to the multispecies complexity of the fisheries in the Kattegat-Skagerrak and the North Sea and the mechanical properties of the trawl netting during the fishing process, it is not possible to achieve perfect size or species selection. Some bycatch will always occur in towed fishing gears. However, there is little doubt that current levels of discard of some towed fisheries can be improved. A large number of selective fishing gears have been tested over the two decades. Several of these studies used methods and procedures for which the results obtained only apply to the specific case study. Such results can not be transferred to other areas with other populations. Studying selectivity in fishing gear should be done systematically, such that the results have a broad applicability and good predictive power.

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Paper 1



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Evaluation of a simple means to reduce discard in the Kattegat-Skagerrak *Nephrops* (*Nephrops norvegicus*) fishery: Commercial testing of different codends and square-mesh panels.

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Evaluation of a simple means to reduce discard in the Kattegat-Skagerrak *Nephrops* (*Nephrops norvegicus*) fishery: Commercial testing of different codends and square-mesh panels

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Abstract

Discarding of fish species in the Kattegat-Skagerrak *Nephrops* directed fisheries remains at high levels. In this work we have tested four sets of codends pair-wise with the catch comparison technique under full commercial conditions to assess their potential in reducing the catch of undersized commercial species, in particular cod. We investigate the position of a 90 mm square-mesh panel (SMP), the effect of increasing the mesh size from 90 to 120 mm in the SMP, the effect of inserting a 90 mm SMP in an 80 mm codend and the effect of increasing the codend mesh size from 90 to 120 mm in a total of 89 hauls. Inserting the SMP 3–6 m from the codline compared to 6–9 m from the codline, reduced catches of cod above the minimum landing size (MLS) and *Nephrops* above and below the MLS. Increasing the mesh size in the SMP from 90 to 120 mm increased the catch of cod above the MLS in weight with an overall increase of 12% in the revenue. The effect of installing a 90 mm SMP 6–9 m from the codline in a nominal 80 mm codend had no effect on the catch of cod. Increasing the nominal codend mesh size from 90 to 120 mm reduced the catch of all species below the MLS, except monkfish. Catches of *Nephrops* above the MLS were, however, reduced by approximately one third and the total loss in revenue was 21%.

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Keywords: Species selectivity; *Nephrops norvegicus*; Trawl; By-catch; Discard; Kattegat; Skagerrak; Square-mesh panel

1. Introduction

Discard sampling programmes have identified a high discard rate of commercial species in the Kattegat-Skagerrak *Nephrops* (*Nephrops norvegicus*) directed fishery (Anon., 2003). By-catch and discard of cod (*Gadus morhua*) call for particular attention because the stock is at a critically low level (ICES, 2006). In parts of the North Sea, the selectivity for cod has been improved by introducing a 120 mm codend in the legislation for selected fisheries (EC Reg. No. 2056/2001). The actions in the Kattegat-Skagerrak area have been less dramatic and at the onset of the present experiment, a codend mesh size of 70 mm was allowed in combination with an 80 mm square mesh panel (SMP) (EC Reg. No. 850/98). However, reports from Danish fishermen and results from discard sampling (unpublished) indicated that this measure was not sufficient to solve the severe discard problems in the *Nephrops* directed fishery.

Although SMPs are used in several *Nephrops* fisheries, relatively few selectivity studies have been published on this subject (Briggs, 1992; Armstrong et al., 1998; Madsen et al., 1999). The published studies show data mainly on whiting (*Merlangius merlangus*) (Briggs, 1992; Armstrong et al., 1998; Madsen et al., 1999) and haddock (*Melanogrammus aeglefinus*) (Madsen et al., 1999), while only sparse data are accessible on cod (Madsen et al., 1999) and no data have been published on other by-catch species.

Furthermore, a better understanding is needed of fundamental technical parameters that might influence the effectiveness of an SMP. Studies conducted in *Nephrops* (Armstrong et al., 1998) and whitefish fisheries (Graham and Kynoch, 2001; Graham et al., 2003; O'Neill et al., 2006) indicate that the SMP position influences the selectivity. The effect of a SMP, the mesh size in the SMP, the position of the SMP and the effect of increasing the codend mesh size were investigated in this study.

The acceptance of a new gear by the industry is influenced by the economic consequences for the vessel owner and this aspect has not been sufficiently attended to in the past (Tschernij et al., 2004). The Kattegat-Skagerrak *Nephrops* directed fishery

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is characterised by the importance of the by-catch species. In evaluating the economic consequences of a change in gear, it is therefore important to assess the effect on all economically important species. As prices are strongly size-dependent, even a small loss of larger size groups may have a severe impact on the economics of a gear. On the other hand, a considerable loss of small size groups may be compensated for by a minor increase in catches of larger individuals. It is therefore important to take the size composition of the catch into account when evaluating the economic consequence of a gear change.

Improvement of the selectivity will benefit fish stocks in the Kattegat-Skagerrak because mortalities of discards are typically much greater than escapees (Broadhurst et al., 2006). The overall objective of this study is to reduce the discard in the *Nephrops* directed fishery in Kattegat-Skagerrak by improving the species and size selectivity by simple means that are more likely to be implemented in the legislation, if successful, than more complicated designs. To meet the overall objectives, the focus of this study is: to evaluate the effect of gear change on all species of commercial interest to this fishery, with particular attention to cod; to assess basic parameters that influence the selectivity of an SMP; to investigate the effect of an increase in codend mesh size as an alternative strategy to the SMP, and to evaluate the economic effect. Comparative experiments were chosen using a twin trawl set-up. This allows the experiments to be conducted under full commercial towing and hauling conditions while avoiding using a cod-end cover, which might influence the results (Madsen and Holst, 2002) and is more difficult to handle under full commercial conditions.

2. Materials and methods

2.1. Experimental set-up

Different codend designs were tested and pair wise compared in a series of catch comparison experiments as described by Wileman et al. (1996). The twin trawl set-up had one vessel towing two similar trawls side by side. This set-up allows comparison of two different codends fished under full commercial conditions with regards to towing time and towing speed as well as shooting and hauling practices, which can be a problem when handling codend covers. In this work, a selective codend with either an SMP or a larger codend mesh size was tested against a reference codend. The reference codend had either no SMP or an SMP that, due to its position or mesh size, was expected to be less selective than the selective codend.

2.2. Sea trials

All experimental tows were conducted in August and September 2003 onboard the 294 kW commercial vessel FN 234 *Canopus*. The vessel's own trawls were used. The two identical trawls were combined fish and *Nephrops* trawls, using a nominal mesh size of 90 mm and 336 meshes in circumference was used. A three-warp towing system, with a 630 kg roller clump and two 173 cm long *Skagen* otter boards, was used to tow the gear. The towing rig behind the otter boards consisted of 6 m back strops

and 90 m single sweeps. Scraper chains were used in most tows but were removed in areas where the bottom was too soft. The headline height of the trawls was around 2 m and the spread of the wings of each trawl was about 30–35 m.

The codends were shifted between the starboard and port side every 6th tow to compensate for any side effects.

2.3. Experimental codends

An 80 mm codend mesh size and a 90 mm SMP mesh size were chosen as a baseline in the SMP experiments as 90 mm codends already were used by some of the larger vessels on a voluntary basis. A 90 mm codend was chosen as baseline when

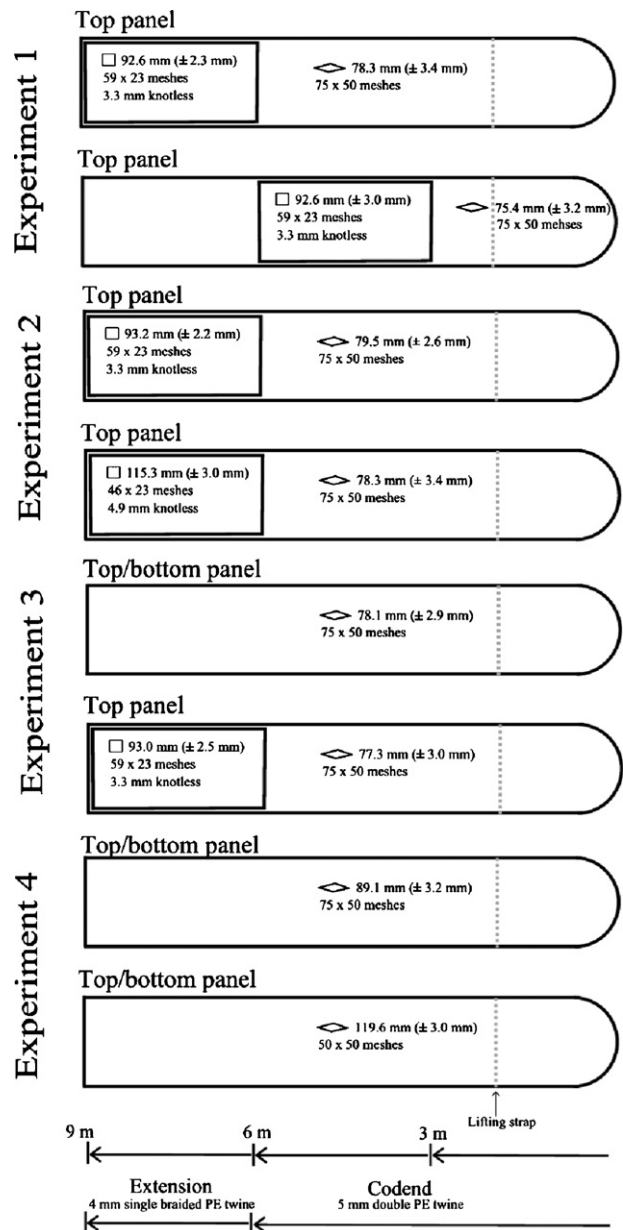


Fig. 1. Top panels of the eight cod-ends used during the experiments. The rectangle indicates where the SMP's are placed. Bottom panels are identical but without windows. The measured mesh sizes (ICES 4 kg wedge) with standard deviation are indicated.

Table 1
Operational conditions for the four experiments

	No. hauls	Towing time (h)		Speed (kts)		Depth (m)		Sea state (m)	
		Avg. \pm S.D.	Range	Avg. \pm S.D.	Range	Avg. \pm S.D.	Range	Avg. \pm S.D.	Range
Experiment 1	24	6.9 \pm 0.8	4.0–7.8	2.5 \pm 0.1	2.2–2.6	143 \pm 46.7	47–261	0.9 \pm 0.6	0.0–2.0
Experiment 2	20	6.8 \pm 0.8	5.2–7.6	2.4 \pm 0.1	2.2–2.6	156 \pm 57.6	38–252	0.9 \pm 0.5	0.2–2.0
Experiment 3	24	7.0 \pm 0.5	5.8–7.5	2.5 \pm 0.1	2.3–2.6	170 \pm 38.6	117–261	0.5 \pm 0.3	0.1–1.5
Experiment 4	21	7.0 \pm 0.6	5.3–8.0	2.5 \pm 0.2	2.2–2.6	190 \pm 46.9	117–261	0.6 \pm 0.4	0.0–1.7

Avg.: average per haul, S.D.: standard deviation per haul.

investigating a codend mesh size increase as an alternative to SMPs. The 90 mm codend was compared to a 120 mm codend similar to those used in selected parts of the North Sea (EC Reg. No. 2056/2001).

Specifications for the codends used in the four experiments are shown in Fig. 1. When an SMP was used, it was inserted in the top panel with two open diamond meshes between the SMP and the adjacent selvages. In all cases, the joining ratio was two diamond meshes to one square mesh. All codends and extensions had 100 open meshes in circumference and 4 meshes in each selvedge. The length of the extension pieces and codends were kept constant at 3 and 6 m respectively.

2.4. Experimental recordings

Operational conditions were recorded for each haul. Depth, speed and sea state were recorded at the beginning and end of the haul and average values were calculated. The sea state was estimated by eye. When the codends arrived at the surface the vessel speed was increased from about 2.5 to 4 knots, which is standard commercial practice owing to the large quantities of clay and mud in this fishery.

The vessel's fish-hold was divided into two, one for each codend. The catch was sorted into four categories: important species for consumption (*Nephrops*, cod, witch (*Glyptocephalus*

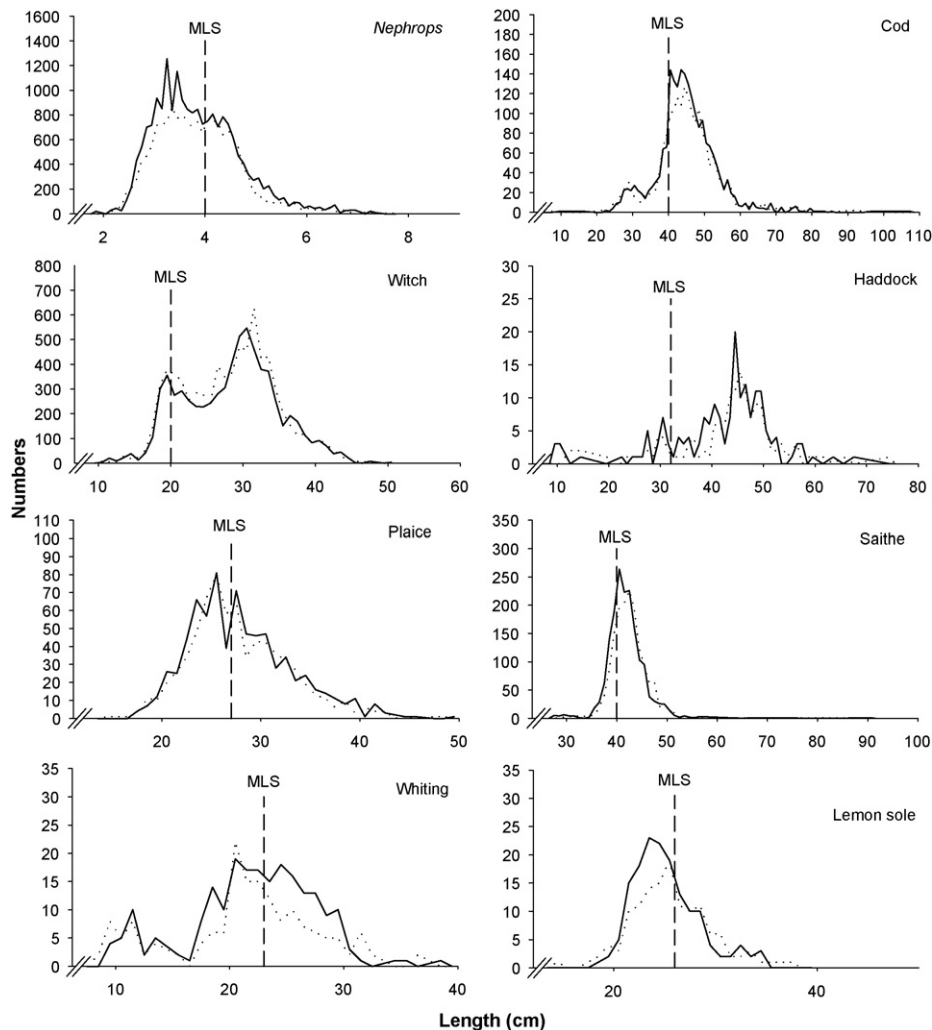


Fig. 2. Catches in experiment 1. The 6–9 m window is indicated by the solid line and the 3–6 m window by the broken line. *Nephrops* are given in carapace length.

cynoglossus), plaice (*Pleuronectes platessa*), saithe (*Pollachius virens*), haddock, lemon sole (*Microstomus kitt*), monkfish (*Lophius piscatorius*) and whiting), other species for consumption (primarily ling (*Molva molva*), tusk (*Brosme brosme*), pollack (*Pollachius pollachius*), wulf-fish (*Anarhynchus lupus*), halibut (*Hippoglossus hippoglossus*) and spurdogs (*Squalus acanthias*)), other fish (fish of no commercial value, primarily blue whiting (*Micromesistius poutassou*), and thorny ray (*Raja radiata*)) and debris. The latter three categories were weighed, whereas the commercially important species were length measured to the centimetre below and the carapace length of *Nephrops* was measured to the mm below with an electronic calliper. In the subsequent analysis, 0.5 cm was added to all length classes of fish and 0.5 mm was added to all length classes of *Nephrops*. The total catch of the economically important species was measured in all tows except for *Nephrops* and witch,

which were frequently sub-sampled owing to large catches of these two species. About 250–500 *Nephrops* and 100–300 witches were measured from each codend during sub-sampling.

Fifty meshes in each codend and SMP were measured in a dry condition before the sea trials and in a wet condition after the sea trials, using an ICES gauge and 4 kg tension setting (Wileman et al., 1996). Measurements taken with a legal EC wedge gauge (5 kg hanging weight) would be approximately 3.9% higher (Ferro and Xu, 1996).

2.5. Catch comparisons

Catch weights of the commercially important species were estimated using monthly specific conversion factors from Coull et al. (1989) for fish species and sex-specific conversion factors for *Nephrops* from ICES (1995). Catch numbers and gutted

Table 2
Results in experiment 1

	SMP 6–9 m	SMP 3–6 m	Difference	N	W statistic	P-value
<i>Nephrops</i>						
Total No.	19735	16458	–16.6%	894	–65898	<0.001
No. <40 mm	12015	9676	–19.5%	556	–16769	0.021
No. ≥40 mm	7719	6782	–12.1%	341	–14562	<0.001
kg ≥40 mm	578	485	–16.1%	552	–17411	0.016
Cod						
Total No.	2094	1900	–9.3%	743	–16193	0.085
No. <40 cm	423	420	–0.7%	240	–172	0.919
No. ≥40 cm	1671	1480	–11.4%	502	–10687	0.043
kg ≥40 cm	2008	1868	–7.0%	502	–8163	0.129
Witch						
Total No.	6945	7496	7.9%	575	18563	0.010
No. ≥20 cm	910	976	7.3%	464	15592	0.003
Plaice						
Total No.	756	715	–5.4%	359	217	0.942
Saithe						
Total No.	1687	1555	–7.8%	358	–4924	0.132
No. <40 cm	463	320	–30.9%	118	–1583	0.006
Haddock						
Total No.	176	139	–21.0%	200	–2953	0.022
No. ≥32 cm	148	119	–19.6%	161	–149	0.050
kg ≥32 cm	120	68	–43.3%	107	–1704	<0.001
Whiting						
Total No.	217	162	–25.3%	89	–1046	0.009
No. ≥23 cm	103	63	–38.8%	54	–588	0.003
kg ≥23 cm	15	9	–35.3%	55	–499	0.016
Lemon sole						
Total No.	156	135	–13.5%	140	–606	0.429
Monkfish						
Total No.	22	21	–4.5%	44	–22	0.884
Other fish, consumption						
Total kg	159	139	–12.6%	25	–82	0.247
Other fish, discard						
Total kg	1567	1590	1.5%	25	4	0.966
Debris						
Total kg	1756	1797	2.3%	23	–20	0.773

Species are divided by the MLS and the P-value is indicated. N is the number of comparisons. W is the Wilcoxon statistic.

catch weights were examined. For *Nephrops*, cod, witch, plaice, saithe, haddock, whiting and lemon sole, data were divided into fractions below and above the species-specific minimum landing sizes (MLS). Monkfish (*Lophius piscatorius*) is only given in numbers and total weight because there is no MLS for the species in Kattegat-Skagerrak. Witch has no MLS but we have used a functional MLS of 20 cm, under which the gutting is too cumbersome compared to the price of the fish.

Differences between catch in the two codends were tested using a Wilcoxon signed-ranks test (Sokal and Rohlf, 1997). This test was chosen because violation of the underlying assumption of normality behind the paired *t*-test may lead to an erroneous conclusion (Smith, 1995). The Wilcoxon test only assumes a symmetric distribution of the difference and is therefore more robust, but at the cost of a slight loss of power in cases where data are normally distributed (Smith, 1995). To use the maximum information in the data set, the observations for each length class were compared for each haul.

2.6. Economic evaluation

An economic evaluation of the different gear changes was performed on the assumption that all individuals above the MLS could be landed.

Thus all individuals of marketable length of the commercially important species were used to assess the gross value of the landed catch:

$$V = \sum_{i=1}^m \left\{ \sum_{j=1}^n (c_{ij} \cdot \alpha_i l_j^{\beta_i} \cdot f_i(l_j)) \right\} \quad (1)$$

where *V* is the total value of the catch, *i* represents *m* different species and *j* represents *n* length classes. *C* is the number of fish, *l* is the length of the fish, α and β are constants in the length to weight conversion equation (Coull et al., 1989) and *f*(*l*) is the species-specific relationship between size and price. In experiments such as these, catches of cod often exceed the limited quotas. To compensate for this, the total value of the

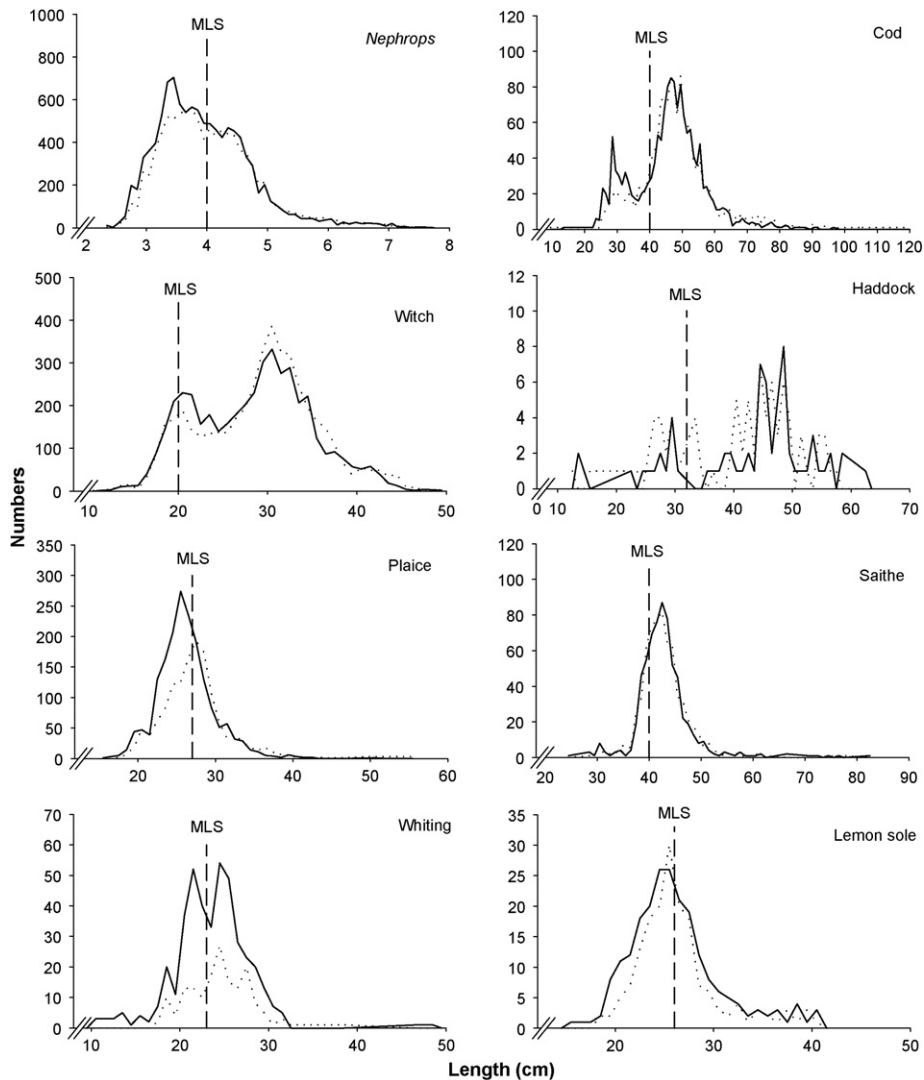


Fig. 3. Catches in experiment 2. The 93.2 mm window is indicated by the solid line and the 115.3 mm window by the broken line. *Nephrops* are given in carapace length.

catch of each gear was also estimated in a scenario where cod is excluded.

The catch was divided into the species-specific size categories defined by EC Reg. No. 2406/96, laying down common marketing standards for certain fishery products. The annual mean prices for 2005 on all fish species and size categories were obtained from the official landing statistics (Anon., 2006). Due to the high MLS on *Nephrops* in Denmark (carapace length = 40 mm), are the size categories different from the ones defined in the EC regulation. For *Nephrops*, we therefore used current prices (November 2006) on the applied size categories provided by the industry.

A small fraction of the catch consisted of marketable fish that were weighed but not measured. This fraction was largely made up of ling, tusk and pollack. The gutted weight was calculated by use of the conversion factor for ling (Coull et al., 1989) and the

non-categorised price for “other gadoids” in the official landing statistics (Anon., 2006) was used in the economic evaluation.

3. Results

3.1. Sea trials

A total of 93 hauls were conducted during the four sea trials with the twin trawl rig; 87 in Skagerrak and 6 in Kattegat. Four hauls were not included in the final analysis owing to damage to the fishing gear. The average values for the operational conditions are provided in Table 1.

The average measured mesh sizes are indicated in Fig. 1. The average shrinkage in the mesh size of the SMP from start to the end of the sea trials was 4.9%, varying from 4.1 to 5.5%, and 5.5% for the standard codend, varying from 3.7 to 7.0%

Table 3
Results in experiment 2

	90 mm SMP	120 mm SMP	Difference	N	W statistic	P-value
<i>Nephrops</i>						
Total No.	10738	9739	−9.3%	840	−35113	0.008
No. <40 mm	6175	5168	−16.3%	277	−9535	<0.001
No. ≥40 mm	4563	4572	0.2%	563	−763	0.918
kg ≥40 mm	331	338	2.1%	562	3374	0.650
Cod						
Total No.	1516	1464	−3.4%	700	1949	0.814
No. <40 cm	391	275	−29.7%	201	−2359	0.060
No. ≥40 cm	1125	1189	5.7%	500	7365	0.141
kg ≥40 cm	1656	1869	12.8%	500	10696	0.039
Witch						
Total No.	4481	4540	1.3%	554	72	0.991
Plaice						
Total No.	1783	1386	−22.3%	270	2345	0.233
No. ≥27 cm	622	720	15.8%	173	3483	<0.001
kg ≥27 cm	174	213	22.7%	173	2157	0.047
Saithe						
Total No.	656	667	1.7%	291	3	0.999
Haddock						
Total No.	70	85	21.4%	120	835	0.195
Whiting						
Total No.	422	164	−61.1%	81	−1625	<0.001
No. <23 cm	188	52	−72.3%	37	−462	<0.001
No. ≥23 cm	234	112	−52.1%	45	−338	0.021
kg ≥23 cm	32	15	−52.4%	45	−368	0.014
Lemon sole						
Total No.	204	160	−21.6%	120	−862	0.138
Monkfish						
Total No.	11	9	−18.2%	21	−21	0.701
Other fish, consumption						
Total kg	158	188	18.6%	21	55	0.246
Other fish, discard						
Total kg	1642	1833	11.6%	21	73	0.145
Debris						
Total kg	1954	1604	−17.9%	13	−59	0.040

Species are divided by the MLS and the P-value is indicated. N is the number of comparisons. W is the Wilcoxon statistic.

3.2. Effect of SMP position

Results from the Wilcoxon test for all four experiments are shown for the comparison of total catches for all species and size categories where they are significant (P value < 0.05). Catches of all categories of *Nephrops* were significantly ($P < 0.05$ and $P < 0.01$) reduced in the codend with the SMP in the aft position (3–6 m) compared to the codend with the SMP in forward position (6–9 m) (Fig. 2 and Table 2). Also, the number of cod above the MLS was significantly reduced ($P < 0.05$) and particularly so for the cod just above the MLS (40–45 cm) (Fig. 2). Haddock and whiting in total number, and in number and weight above the MLS, and saithe in the number below the MLS, were significantly ($P < 0.05$) reduced. A significant increase in catches was found for witch in total number ($P < 0.05$) and the number below the MLS ($P < 0.01$).

There was a total loss in value of 8% with the SMP in the aft position (Table 6). Most of this loss was caused by the reduction in catches of *Nephrops* and cod. When cod is excluded from the analysis, the total loss is 9.3%.

3.3. Effect of SMP mesh size

A significant ($P < 0.05$) reduction in catches in the gear with the large mesh size SMP (115.3 mm) compared to the small mesh size SMP (93.2 mm) was found for: *Nephrops* in total number and the number below the MLS; witch in the number below the MLS; for all categories of whiting and finally for debris (Fig. 3 and Table 3).

A significant increase in catches with the large SMP mesh size was found for: cod in weight above the MLS and for witch and plaice above the MLS in both numbers and weight.

The increased catch of cod and witch above the MLS were the main contributors to a total increase in the value of the catch by 11.5% (Table 6). The significant ($P < 0.05$) increase in catches of plaice as well as a non-significant increase in catches of legal-sized *Nephrops* also contributed to the increased value. The significant reduction in catches of whiting, on the other hand, had only minor impact on the total value due to the small amount and low price of the species. When cod is excluded from the analysis, the total increase in the value of the catch is reduced to 7.6%.

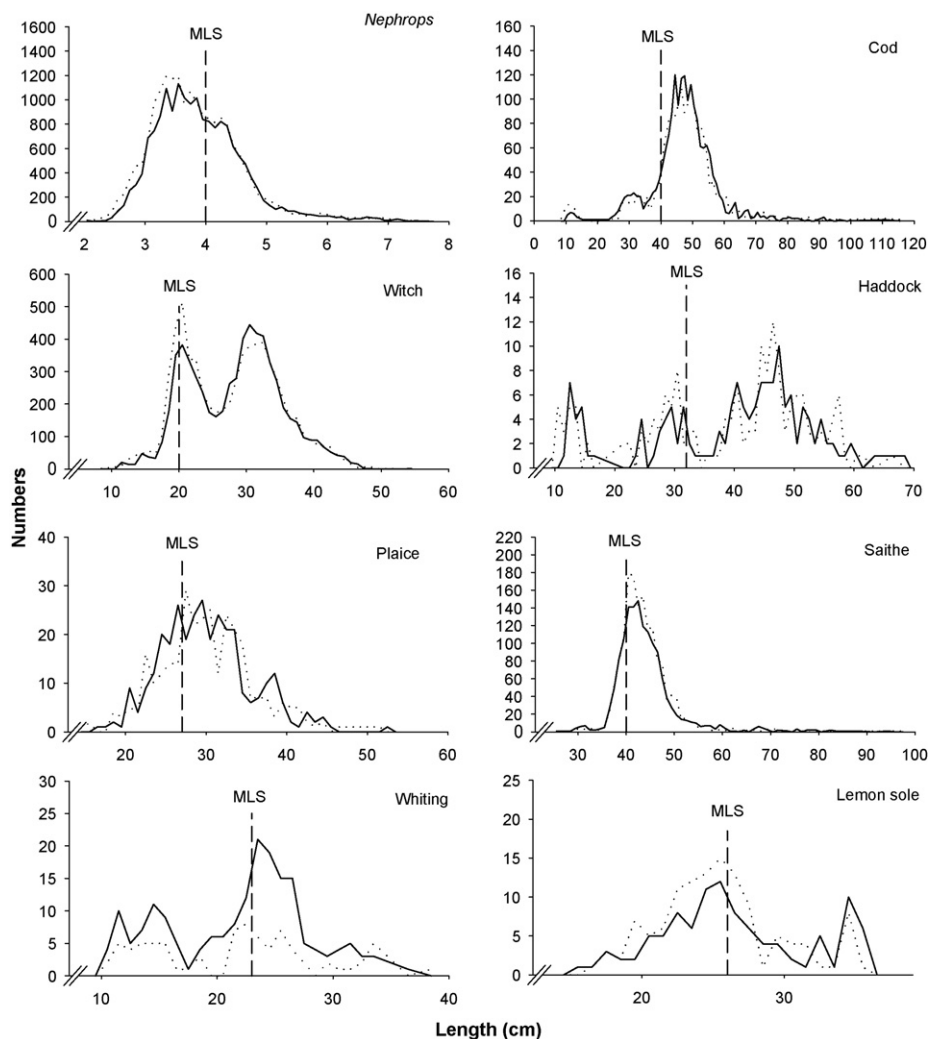


Fig. 4. Catches in experiment 3. The cod-end without window is indicated by the solid line and the cod-end with a 93.0 mm window by the broken line. *Nephrops* are given in carapace length.

3.4. Effect of an SMP

A significant ($P < 0.05$) reduction in catches comparing the codend with an SMP (93.0 mm mesh size) to a codend without an SMP was recorded for: *Nephrops* in total number and number below the MLS; witch in numbers below the MLS; saithe in numbers above the MLS and for all categories of whiting (Fig. 4 and Table 4). Catches of lemon sole in total number, number above and weight above the MLS were significantly ($P < 0.05$) higher in the gear with an SMP than in the gear without.

3.5. Effect of increasing the codend mesh size

A significant ($P < 0.01$) reduction in catches was found in the codend with a larger mesh size (119.6 mm) compared with the

codend with a smaller mesh size (89.1 mm) for: all categories of *Nephrops*, witch, saithe, whiting and lemon sole; cod in total number and number below the MLS; haddock in total number and number below the MLS; plaice below the MLS; discard of other fish and debris (Fig. 5 and Table 5). Catches of haddock, however, were sparse.

The reduction in the economic value of the catches when increasing the codend mesh size was 20.6% (Table 6). Most of this change was due to the significant reduction in catches of *Nephrops* and witch. Though not significant, an increase in the catches of large cod had a positive impact on the value of the catch in the codend with the larger mesh size (Fig. 5). The loss in the total value of the catch increased to 31.1% when cod was excluded from the economic evaluation.

Table 4
Results in experiment 3

	No SMP	90 mm SMP	Difference	N	W statistic	P-value
<i>Nephrops</i>						
Total No.	18882	17250	-8.6%	1040	-81514	<0.001
No. <40 mm	11966	10479	-12.4%	351	-16926	<0.001
No. ≥40 mm	6916	6771	-2.1%	690	-10789	0.294
kg ≥40 mm	487	475	-2.5%	690	-10789	0.294
Cod						
Total No.	1784	1867	4.7%	766	6653	0.496
No. <40 cm	291	307	5.5%	213	96	0.946
No. ≥40 cm	1493	1560	4.5%	554	4401	0.469
kg ≥40 cm	2158	2169	0.5%	554	-118	0.985
Witch						
Total No.	6287	6043	-3.9%	740	-5454	0.585
No. <20 cm	1017	748	-265%	146	-3069	<0.001
Plaice						
Total No.	307	321	4.6%	283	820	0.706
Saithe						
Total No.	1540	1405	-8.8%	502	-9156	0.077
No. ≥40 cm	1255	1113	-11.3%	395	-7520	0.038
Haddock						
Total No.	171	152	-11.1%	217	-1582	0.270
Whiting						
Total No.	184	81	-56.0%	110	2563	<0.001
No. <23 cm	86	46	-46.5%	58	541	0.011
No. ≥23 cm	98	35	-64.3%	53	734	<0.001
kg ≥23 cm	14	6	-57.1%	53	631	0.002
Lemon sole						
Total No.	79	113	43.0%	97	1150	0.010
No. ≥26 cm	22	41	86.4%	41	307	0.012
kg ≥26 cm	5	10	100.0%	41	372	0.005
Monkfish						
Total No.	20	20	0.0%	41	0	0.994
Other fish, consumption						
Total kg	269	272	1.1%	25	10	0.898
Other fish, discard						
Total kg	1939	2103	8.5%	25	60	0.399
Debris						
Total kg	3370	3746	11.2%	19	36	0.442

Species are divided by the MLS and the P-value is indicated. N is the number of comparisons. W is the Wilcoxon statistic.

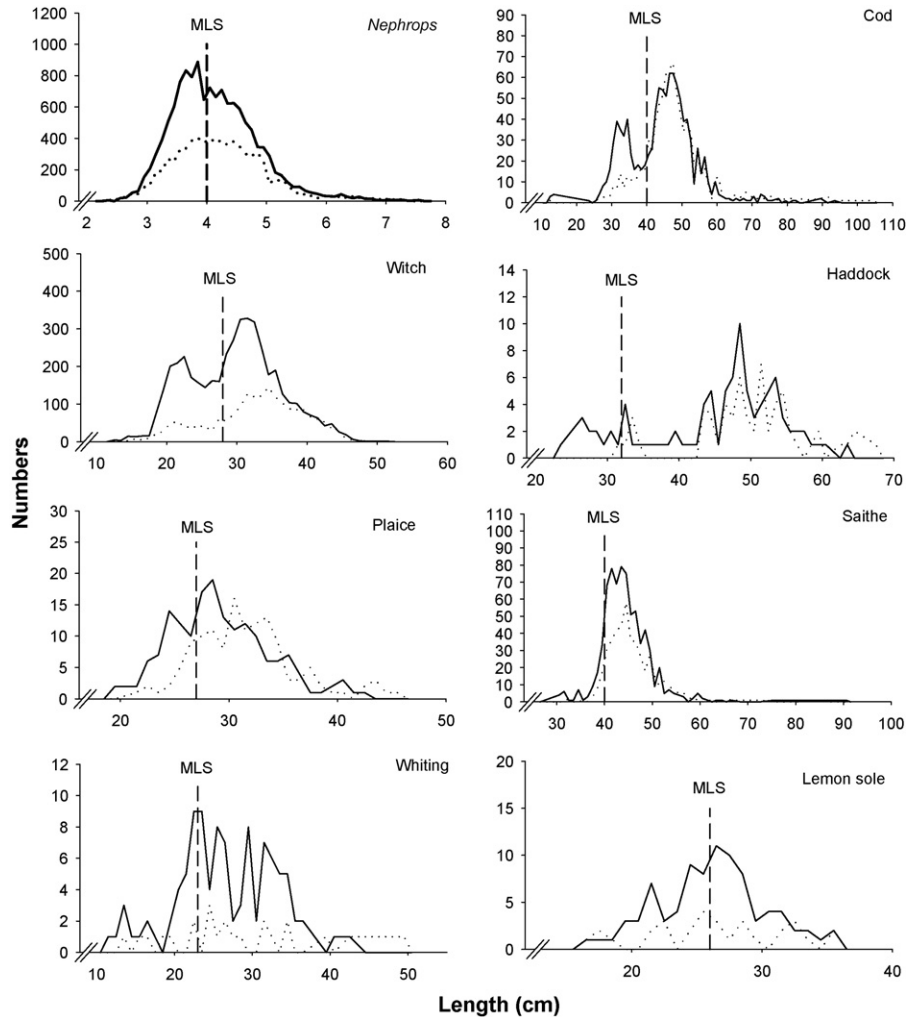


Fig. 5. Catches in experiment 4. The 89.1 mm cod-end is indicated by the solid line and the 119.6 mm cod-end by the broken line. *Nephrops* are given in carapace length.

4. Discussion

The reliability of these comparative experiments is high because hauls are of commercial length. Due to high catch load of small individuals, duration of hauls is usually shortened when using small-meshed control codends or codend covers and this results in relatively small catches in the codend being tested. When testing the performance of a gear, it is important to obtain commercial catches, as codend geometry and thus selectivity may vary with the catch build up (O'Neill and Kynoch, 1996). The disadvantage of the comparative method is that the collected data only allows for estimation of the relative selectivity. Additional selectivity experiments are therefore needed to estimate the absolute selectivity (selectivity parameters), in particular for codends that are now used commercially.

A loss of *Nephrops* with the SMP in the aft-most position was not expected as *Nephrops* primarily have been observed in the lower part of the trawl (Main and Sangster, 1985). One explanation could be that the accumulated catch comes into contact with the SMP and this allows *Nephrops* and other species to escape through the panel.

With regards to the selectivity of round fish, the efficiency of a SMP have previously been found to increase towards the cod line (Graham and Kynoch, 2001; Graham et al., 2003) but conflicting conclusions favouring a position further forward in the trawl have also been drawn (Armstrong et al., 1998; O'Neill et al., 2006). Glass et al. (1993) experimentally demonstrated that fish will try to penetrate the meshes surrounding them when the alternative clearer path is blocked; a situation similar to reaching the codend of a trawl. A rather similar blocking of the clear path may occur further forward in the gear with the dramatically reduced trawl cavity where the last tapered section is joined with the untapered extension. As trawl designs in different fisheries and areas vary, the optimal positions of the SMP may be more affected by the actual gear's design than by the position relative to the gear's cod-line. The optimal position of the SMP may therefore not be valid across different gear designs.

The effect of installing a 90 mm SMP in a codend was surprisingly limited for most species. Increasing SMP mesh size to 120 mm had a marked effect on the catch composition, with fewer undersized individuals of a number of species and higher catches of some of the economically important

Table 5
Results in experiment 4

	90 mm codend	120 mm codend	Difference	<i>N</i>	<i>W</i> statistic	<i>P</i> -value
<i>Nephrops</i>						
Total No.	13183	7408	−43.8%	834	−199320	<0.001
No. <40 mm	6240	3059	−51.0%	263	−24686	<0.001
No. ≥40 mm	6943	4349	−37.4%	572	−81247	<0.001
kg ≥40 mm	487	322	−33.8%	571	−70019	<0.001
Cod						
Total No.	1043	883	−15.3%	377	−11733	<0.001
No. <40 cm	313	130	−58.5%	109	−3855	<0.001
No. ≥40 cm	730	753	3.2%	269	1484	0.487
kg ≥40 cm	948	1059	11.7%	269	3156	0.153
Witch						
Total No.	4486	1879	−58.1%	596	−105808	<0.001
No. <28 cm	275	71	−74.1%	81	−2169	<0.001
No. ≥28 cm	4211	1808	−57.5%	516	−78678	<0.001
kg ≥28 cm	819	472	−42.4%	516	−62809	<0.001
Plaice						
Total No.	167	133	−20.4%	123	−1065	0.096
No. <27 cm	53	20	−62.3%	31	−283	<0.001
Saithe						
Total No.	734	460	−37.3%	297	−14807	<0.001
No. <40 cm	83	31	−62.7%	51	−740	<0.001
No. ≥40 cm	651	429	−34.1%	247	−8995	<0.001
kg ≥40 cm	591	404	−31.7%	247	−7971	<0.001
Haddock						
Total No.	93	61	−34.4%	117	−1506	0.008
No. <32 cm	12	1	−91.7%	14	−77	0.005
No. ≥32 cm	81	60	−25.9%	104	−858	0.069
Whiting						
Total No.	102	24	−76.5%	76	−1816	<0.001
No. <23 cm	30	7	−76.7%	22	−146	0.008
No. ≥23 cm	72	17	−76.4%	55	−941	<0.001
kg ≥23 cm	15	5	−66.0%	55	−790	<0.001
Lemon sole						
Total No.	82	24	−70.7%	66	−1263	<0.001
No. <26 cm	35	14	−60.0%	30	−226	0.008
No. ≥26 cm	47	10	−78.7%	37	−433	<0.001
kg ≥26 cm	13	3	−79.3%	37	−475	<0.001
Monkfish						
Total No.	18	18	0.0%	37	0	0.993
Other fish, consumption						
Total kg	156	131	−15.5%	21	−48	0.388
Other fish, discard						
Total kg	903	445	−50.8%	21	−196	<0.001
Debris						
Total kg	2582	891	−65.5%	20	−184	<0.001

Species are divided by the MLS and the *P*-value is indicated. *N* is the number of comparisons. *W* is the Wilcoxon statistic.

species. Increased catches of larger individuals in selective fishing gears have also been observed in other experiments (Madsen et al., 2006). The reason for this is not clear, but an improved water flow through the gear, due to the use of panels with a larger mesh size, may improve the catch efficiency of larger fish.

The increase in codend mesh size from 90 to 120 mm caused a greater reduction in catches of cod below the MLS than did

the SMPs. Large catch losses were, however, observed for most of the economically important species caught in the fishery.

Though not as efficient in reducing the discard as an increase in codend mesh size, installing a SMP still increases the chance of escape for undersized fish while loss in catches of species like *Nephrops* and witch are kept low. Of the gear types tested, the SMP is therefore estimated to be the best choice for the *Nephrops* directed fishery in question. But due to the critical level of the

Table 6
Estimated catch values

	Exp. 1: SMP position			Exp. 2: SMP mesh size			Exp. 3: SMP effect			Exp. 4: mesh size		
	6–9 m	3–6 m	Difference	90 mm	120 mm	Difference	No SMP	SMP	Difference	90 mm	120 mm	Difference
<i>Nephrops</i>	5531	4494	–18.7%	3090	3200	3.6%	4507	4365	–3.2%	4436	3043	–31.4%
Cod	4333	4132	–4.6%	3749	4442	18.5%	5157	5002	–3.0%	2102	2555	21.6%
Witch	3487	3619	3.8%	2275	2563	12.7%	3305	3343	1.1%	2678	1688	–37.0%
Plaice	282	250	–11.2%	347	434	25.2%	178	174	–2.2%	78	87	11.8%
Saithe	661	674	1.9%	311	307	–1.3%	808	758	–6.1%	429	291	–32.2%
Haddock	172	160	–7.1%	75	78	3.9%	157	146	–6.7%	120	104	–13.1%
Whiting	11	7	–30.8%	23	11	–51.7%	11	5	–57.5%	12	4	–64.8%
Lemon sole	57	60	4.7%	67	65	–2.6%	20	40	104.9%	50	11	–78.7%
Monk fish	553	492	–11.1%	266	258	–2.8%	370	309	–16.5%	410	395	–3.8%
Other fish	215	187	–12.6%	214	254	18.6%	365	369	1.1%	211	178	–15.5%
Total	15301	14075	–8.0%	10416	11613	11.5%	14877	14510	–2.5%	10526	8356	–20.6%
Total ^a	10968	9943	–9.3%	6666	7170	7.6%	9719	9508	–2.2%	8424	5801	–31.1%

Prices in Euro.

^a Without cod.

cod stock in the Kattegat-Skagerrak (ICES, 2006), the selectivity of cod both above and below MLS should be further improved. The effect of a further increase of SMP mesh size should thus be tested and ways to avoid the loss of *Nephrops* when the SMP is placed in an aft position should be examined.

The economic consequences of improving the selectivity of fishing gears are seldom addressed in selectivity experiments. However, the most common reason that dissuades fishermen from adopting new selective designs is the prospect of a short-term loss of landings (Tschernij et al., 2004; Catchpole et al., 2005). Unless the fishermen are financially compensated when changing to a more selective gear, they are likely to change their behaviour to minimise the economic loss. Such changes could be to target fish that are more efficiently retained by the larger mesh size than *Nephrops* and witch, or to increase the effort to compensate for the catch loss or, finally, to make use of legal or illegal means to reduce the selectivity of the trawl. In this study we found that the economic consequences of the tested SMPs were considerably less severe than the alternative of increasing the codend mesh size. The 120 mm SMP was introduced in Kattegat-Skagerrak in 2005, and use of the panel is rewarded with 3 additional days at sea (EC Reg. No. 15238/04). Most vessels use the SMP today and major problems as experienced in the Baltic Sea, where high short-term loss led to gear manipulation (Suuronen et al., 2007), have not been observed.

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Paper 2



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Prediction of selectivity from morphological conditions: Methodology and a case study on cod (*Gadus morhua*).

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Prediction of selectivity from morphological conditions: Methodology and a case study on cod (*Gadus morhua*)

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ABSTRACT

The FISHSELECT methodology, tools, and software were developed and used to measure the morphological parameters that determine the ability of cod to penetrate different mesh types, sizes, and openings. The shape of one cross-section at the cod's head was found to explain 97.6% of the mesh penetration results obtained in a laboratory experiment. Design guides predicting the 50% retention length (L50) of different mesh types, sizes, and openings were produced and compared with results from sea trials. Results show that the morphology-based simulations can be used to explain both the within-haul and the between-haul variations previously reported from sea trials. Finally, based on the results obtained, ideas to improve the size selection of cod in towed gear are presented.

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1. Introduction

Cod (*Gadus morhua*) is economically one of the most important species targeted in the northeast Atlantic trawl fisheries. However, several of the cod stocks inhabiting this region have in recent years been at critically low levels (ICES, 2006). To aid recovery of the cod stocks, several technical measures have been tested and some of these have been implemented in legislation. Examples of these measures are square mesh panels and an increase in codend mesh size, both of which are expected to improve the size selectivity of cod (Madsen et al., 1999, 2002; Kvamme and Isaksen, 2004; Madsen and Stæhr, 2005; Krag et al., 2008).

Diamond mesh netting is the commonly used mesh type in towed gear in the northeastern Atlantic. When the size selectivity for cod in diamond mesh codends is estimated experimentally (e.g., in Galbraith et al., 1994), the selection ranges (SR) for single hauls often are relatively large. A large SR value is likely to reflect a large within-haul variation in the selection process. This will, depending on the allowed minimum landing size, increase the risk of catching undersized individuals or losing marketable sizes. Even if individual SR values are small, there can be a problem if the between-haul variation in the 50% retention length (L50) is large. High between-haul variation in L50 has previously been reported on cod in covered codend experiments (e.g., in Dahm et al., 2002).

The effect on size selectivity of technical measures often is assessed through experimental fishing or by discard sampling from the commercial fishery. These time-consuming trial-and-error methods often lead to insufficient knowledge about the selection processes for different species and fisheries. We believe it would be a better starting point to theoretically assess the mesh sizes and shapes required to make it at least morphologically possible for unwanted species or sizes to penetrate the meshes before the gear is constructed and tested at sea. Broadhurst et al. (2006) also proposed this view.

In previous selectivity studies, maximum girth has been the main measure used to relate fish morphology to their ability to pass through meshes (Santos et al., 2006; Tosunoglu, 2007). However, due to differences in deformability of muscle tissue, gut, and bone structures such as the skull, we believe that maximum girth is inadequate to explain the relationship between fish morphology and mesh penetration in towed fishing gear. In the current study we developed a new methodology, FISHSELECT, that includes tools and software to investigate conditions for mesh penetration. The FISHSELECT methodology is a framework that assesses the morphological conditions that determine a fish's ability to physically penetrate a given mesh in a towed fishing gear. The method is based on a combination of laboratory experiments with fish, data collection, data analysis and computer simulations. Besides being a new approach towards providing information for both current and future gear designs and fisheries management, we expect the above methodology to provide information that will extend the use of the codend selectivity simulator PRESEMO (Herrmann, 2005a,b) to enable it to work with species other than round fish and mesh shapes other than diamond-shaped.

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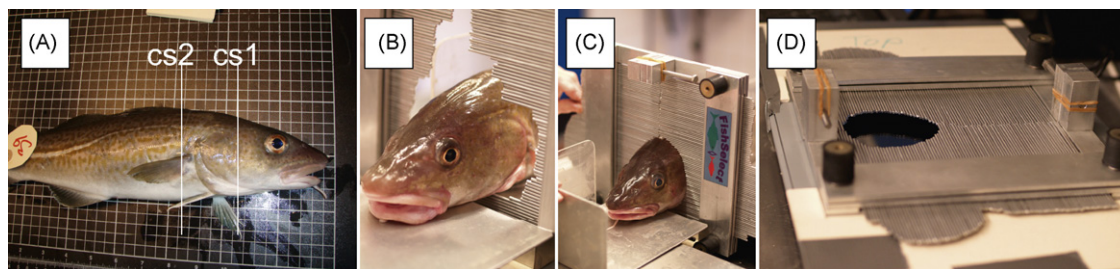


Fig. 1. Positions of CS1 and CS2 on a cod (A) and the measurement (B and C) and scanning of a cross-section shape (D) using the mechanical sensing tool MorphoMeter and a flatbed scanner.

Using the FISHSELECT methodology, we predicted the selective properties for cod in diamond and square mesh shapes and sizes that cover a wide range of values used globally in the commercial fleets. Furthermore, the present examination also included hexagonal and rectangular meshes. We use the results obtained here to explain the variation in estimated selectivity parameters for the same fishing gear used in different experiments, and we suggest how within-haul and between-haul variation could be reduced.

2. Material and methods

2.1. The FISHSELECT methodology

The FISHSELECT methodology involves the following activities:

- (i) The first step of the FISHSELECT methodology is to investigate and quantify the external morphological features of the species in question. The length and weight of each fish is recorded and the positions along the length axis of the fish that are expected to affect its ability to penetrate different meshes are identified. At these positions, the transverse cross-section shapes are extracted with a MorphoMeter, a mechanical sensing tool, and then digitized using a flatbed scanner and subsequent digital image analysis.
- (ii) In subsequent fall-through trials, each fish is presented to a series of stiff mesh templates representing different sizes and shapes of meshes. The results, whether or not the fish is able to fall through the mesh templates, are collected.
- (iii) Then the modeling and simulation functions of the FISHSELECT software are used to combine the measured cross-section data with information about the geometry of the mesh templates

to simulate the fall-through trials. Subsequently, the experimentally obtained fall-through results are compared with the simulated fall-through results using various penetration models; the “best penetration model” is determined by investigating the degree of agreement (DA) between the two sets of results. The penetration model is capable of including either a single cross-section or a combination of several cross-sections in the simulation, and each cross-section shape can be simulated to compress during mesh penetration.

- (iv) Finally the best penetration model is run on a virtual population of fish with assumed morphological properties based on the measurements, and the output is used to predict basic selective characteristics of new and existing netting designs.

The above list of activities is further elaborated in the following sections.

2.2. Fish used

Several physiological processes that may change the cross-section shapes and their deformability start as soon as the fish dies. Therefore, all measurements were conducted on fresh fish. In February 2007, a total of 150 cod were caught by jig and gillnet in Skagerrak and the fish were transferred live to holding tanks on land. Seventy-five cod in the length range of 29–72 cm were selected and used in the experiment. All cod were caught in shallow water (10–20 m) to avoid excessive dilation of the swim bladder. Five fish at a time were taken from the holding tank and killed immediately before the measurements in a strong solution of ethylene glycol mono-phenylether ($C_6H_{10}O_2$), which is commonly used to anaesthetize fish. Each fish was given a unique identification

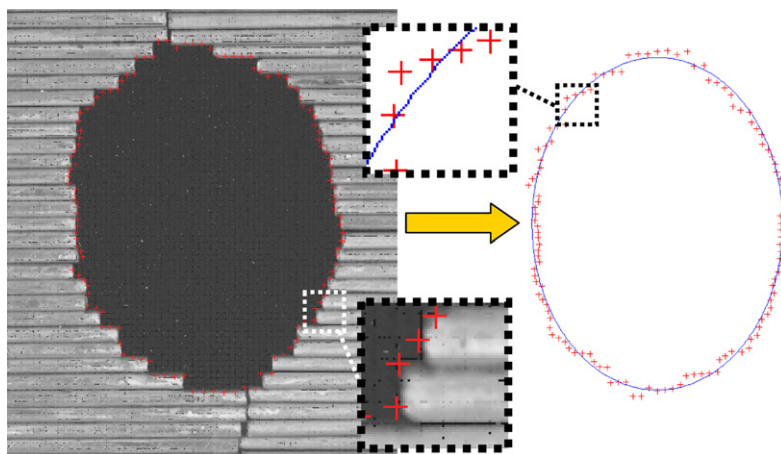


Fig. 2. Example of a scanned MorphoMeter image with a mechanical replica of the outer cross-section contour of a cod (left picture). The crosses are digitized points along the contour detected by contour acquisition routines implemented in the FISHSELECT software. The bottom blow-up picture shows part of the digitized contour and the individual MorphoMeter sticks in greater detail. The right picture shows the fit of an ellipse to the digitized contour with the top blow-up picture showing details.

Table 1
Data for the 118 different mesh templates used in the fall-through experiments.

Mesh type	Mesh size (mm)										
	70	80	90	100	110	120	130	140	160	180	200
Diamond (oa)											
15									x	x	x
20				x	x	x	x	x	x		
25			x			x			x		
30		x	x			x			x		
35			x			x			x		
40			x			x			x		
45			x			x			x		
50			x			x			x		
55		x	x	x	x	x	x	x	x	x	x
60			x			x			x		
65			x			x			x		
70			x			x			x		
75			x			x			x		
80			x			x			x		
85		x	x	x	x	x	x	x	x	x	x
90 ^a	x	x	x	x		x		x	x	x	x
Hexagonal (oa)											
143.6	x	x		x		x		x	x		x
128.3	x	x		x		x		x	x		x
106.3	x	x		x		x		x	x		x
88.9	x	x		x		x		x	x		x
Mesh type	Mesh bar <i>b</i>										
	70	80	90	100	110	120	130	140	160	180	200
Rectangular (bar <i>a</i>)											
10			x			x					x
15			x			x					x
20			x			x					x
30			x			x					x
50			x			x					x
70			x			x					x

Mesh size and the mesh opening angle (oa) are given. *a* and *b* refer to bar lengths. The hexagonal meshes in the table are described by only two parameters (oa and *k*) because the mesh bar (*b*) in this study is given as $k/2$ for all hexagonal meshes (see Fig. 3). For hexagonal meshes *x* refers to *k*. For rectangular meshes all combinations of *a* and *b* are included. For example, for bar length $b = 10$ mm, three different meshes were made: $a = 90$ mm, 120 mm, and 200 mm.

^a Equals square mesh.

number and its length and weight data were recorded. In addition to the 75 fish used in the full-scale experiment, 20 fish were used in initial pilot experiments.

2.3. Initial experiments

The pilot study was conducted to identify where along the cod's length axis the cross-section shapes should be measured. These experiments involved both fall-through experiments and measurements of cross-section shapes. Both procedures are described below. Two cross-sections (CS) were identified for cod: CS1 represented the maximum width and CS2 the maximum height and girth of the fish (Fig. 1A).

2.4. Measurement of cross-section shapes

We developed a mechanical sensing tool, the MorphoMeter that was used to measure cross-section shapes of each cod (Fig. 1). The MorphoMeter consists of adjustable round aluminium sticks that are mounted close together but can move individually with slight friction. To take measurements, a fish was placed in the MorphoMeter perpendicular to the sticks. The position of the cross-section along the length of the fish was predefined (Fig. 1A). The sticks of the MorphoMeter were then moved manually into contact all the way around the circumference of the fish (Fig. 1B and C), leaving a contour of the cross-section shape in the MorphoMeter. Afterwards, the MorphoMeter was scanned on a flatbed scanner (Fig. 1D) to obtain an image of the cross-section shape.

2.5. Estimation of cross-section shape

The image analysis function of the FISHSELECT software was used to extract and digitize the cross-section shapes from the scanned image. Typically, this resulted in a contour represented by about 120 points along the perimeter (Fig. 2). To simplify the descriptions of the cross-section shapes, an elliptical shape was fitted to the points using the software's least-square fitting method (Fig. 2). An ellipse can be described by two parameters; height and width. The morphological relationships between the fitted cross-section shapes and the length of the fish therefore can be established by fitting the regression functions ($p_i = a_i \times l^{b_i}$; $p_1 = \text{width}$, $p_2 = \text{height}$, and $l = \text{length}$) to the data using a least square algorithm in the software. Due to the large number of fish investigated, the variance of the different relationships also could be simulated; this was done by assuming that the variation between individuals could be described by variation in the value of parameter a_i .

2.6. Fall-through experiments

Fall-through experiments were conducted with 118 different stiff mesh templates cut out in 5 mm thick nylon plates (Table 1; Fig. 3). The use of stiff mesh templates is justified by assuming that the hydrodynamic drag acting on the codend results in a tension in the mesh bars that makes it unlikely that a fish can distort the mesh shape when it attempts to pass through during most parts of the fishing process (Efanov et al., 1987; Herrmann and O'Neill,

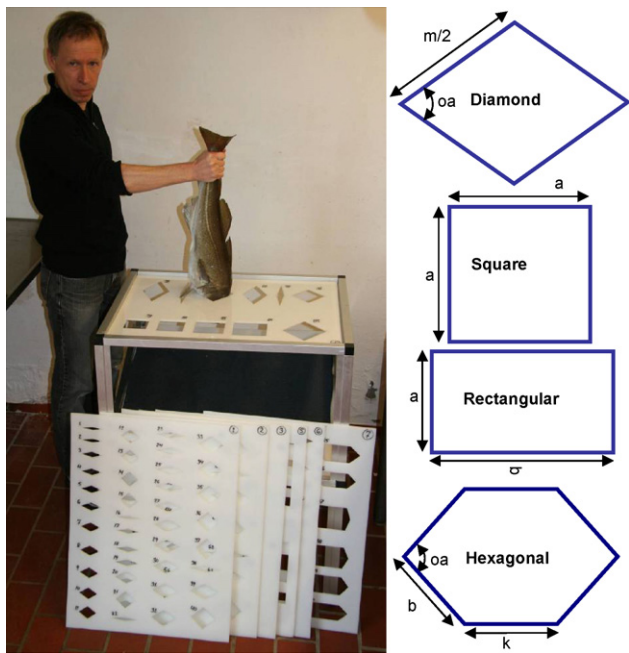


Fig. 3. Fall-through experiments with a cod. Right: the four basic parametric mesh shapes implemented in the software.

2005, 2006). The increased use of thicker and stiffer twine material in codend nettings in many European trawl fisheries supports this assumption.

Four different mesh types (diamond, square, rectangular, and hexagonal) were tested in the fall-through experiment (Table 1; Fig. 3). Each fish was held by the tail and lowered to each of the 118 mesh templates head first. The template plates were kept horizontal and each fish was rotated optimally for falling through the mesh. Gravity was the only force acting on the fish as they encountered the mesh templates. The success or failure in falling through the mesh was recorded for each fish and mesh. A total of 8850 fall-through experiments were performed with the 75 cod and the 118 mesh templates used in this study.

2.7. Repeated experiments

The reliability of the results of the above experiments requires that the cross-section shapes of the fish are not affected by the extensive handling and mechanical contact with the different mesh templates. Three subsequent fall-through trials using all 118 mesh templates were therefore conducted with two fish. The lengths of the two fish were 46.6 and 42.5 cm. On a third cod, the cross-section shapes of CS1 and CS2 were measured both before and after a complete fall-through trial. Cross-section measurements were otherwise always taken before the fall-through experiments in order to measure the fish in its best possible condition. Finally, CS1 and CS2 values for one cod were measured ten successive times to estimate the accuracy of the MorphoMeter.

2.8. Simulation of mesh penetration and selection of a penetration model

The FISHSELECT software tool includes a flexible simulation model with different options for describing and identifying the conditions resulting in successful mesh penetration using data describing fish cross-section shapes and the mesh geometry. Appendix A outlines the mathematical description for the core algorithms implemented.

To select a proper penetration model for cod, we simulated the fall-through experiments with different models assuming different levels of symmetrical and asymmetrical compression of the fitted parametric cross-section shapes. For an elliptical cross-section shape, a symmetrical compression of, for example, 10% is simulated by reducing the width and height of the ellipse by 10% compared to the measured non-compressed cross-section shape. An asymmetrical compression is simulated by reducing the width and height of the ellipse by different percentages. The DA value will vary between 0% and 100%, where 100% is full agreement between all of the 8850 experimental fall-through results and the corresponding simulated results.

In addition to identifying the cross-sections that may be limiting factors in the ability of cod to penetrate different meshes, the results of the fall-through trials also indicated how much the cross-section shape was compressed. In FISHSELECT, compression is defined as the ability of the fish to deform its cross-section shape during a stiff mesh penetration under the pull of gravity. During the fall-through experiments, we observed that if the head of the cod passed through the mesh template, then the entire fish went through with relative ease. For the sake of completeness, when searching for the best penetration model, the fall-through simulations were initiated by checking models including both CS1 and CS2. Subsequently, models based either on CS1 (head) or CS2 (body) were tested. For each simulation, the DA between experimental and simulated results was calculated. The initial simulations assumed symmetric compression for CS1 and CS2. However, comparison with the experimental results indicated that a more asymmetric compression might take place during mesh penetration. CS1 on the head of the fish covers both soft muscle tissue and the harder bony structures of the cranium, and these are likely to be compressed differently during mesh penetration. The deformability of the tissues covered by CS2 was more uniform and, when included in the penetration model, this cross-section shape was subjected to symmetric compression only.

Besides simulating whether or not the fish is able to penetrate the mesh, the FISHSELECT software tool also produces a scaling factor (sf), which indicates how close the simulated fall-through trial is to the borderline between success and failure (see Appendix A). The sf at the borderline is given the value 100%. The simulated fall-through trials that are inconsistent with the experimental results can thus be ranked by how far from correct they are. Comparing the distribution of the sf values for the disagreeing results for different penetration models was a useful exercise, as the range of values and the symmetry of their distribution disclosed whether we assumed too much or too little compression of the fish cross-section shapes. The penetration model that produced the highest DA value was deemed the best penetration model and was used for further analyses.

2.9. Design guides

Once the best penetration model was established, we conducted simulations to predict the basic selective properties, L50 and SR, for the four different mesh types. We defined the basic selection properties for a mesh panel as the selection properties that take only the morphological condition for mesh penetration into account. We are thus representing the selective potential of the mesh panel, without considering any behavioral effects. To estimate L50 and SR for a specific mesh, we first defined its shape and size, then we created a virtual fish population with a suitable size structure, and finally we simulated, for each fish in the population, whether or not it could penetrate the mesh. The empirically established relationships between fish length, the cross-section shape parameters, and their variations were used to define the properties of the fish in the virtual population. To obtain a sufficient number of fish in the

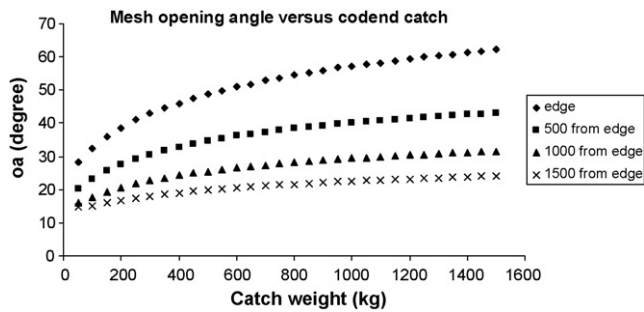


Fig. 4. Calculated opening angles (oa) based on data from Herrmann et al. (2007b) vs. cod-end catch weights at four different distances (in mm) from the catch edge in the cod-end. The calculations are based on a diamond mesh cod-end with 100 open meshes in the circumference and with a mesh size of 110 mm made of double 4 mm polyethylene (PE) twine.

entire selective range of all investigated meshes, the population was generated by drawing 2000 samples randomly from a uniform size distribution. The length range of this population of cod was 2–80 cm. By assuming a logistic selection curve and treating the simulated penetration data for each mesh as covered codend size selection data (Wileman et al., 1996), we estimated L50 and SR with the built-in function of the FISHSELECT software.

The basic selective properties for each mesh type were collected in a design guide, which is a plot showing simulated L50 as iso-curves for a relevant range of mesh sizes versus mesh openings for each mesh type. The mesh openings for diamond and hexagonal meshes are given by the opening angle (oa) and as a squareness factor ($=100 \times (a/b)$) (SFA) for rectangular meshes (see Fig. 3). Square mesh represents a special case of each of the other mesh types, thus square mesh data are included in the diamond mesh design guide ($oa = 90^\circ$), in the rectangular mesh design guide ($SFA = 100\%$), and, finally, in the hexagonal mesh design guide ($oa = 180^\circ$). For hexagonal meshes, only designs for which $b = 0.5 \times k$ were considered in this study (see Fig. 3).

2.10. Simulation of experimental results from sea trials: within-haul variation

To evaluate the relevance of results obtained using the FISHS-ELECT methodology we compared them with similar results from sea trials. Galbraith et al. (1994) reported L50 estimates of 29.2 and

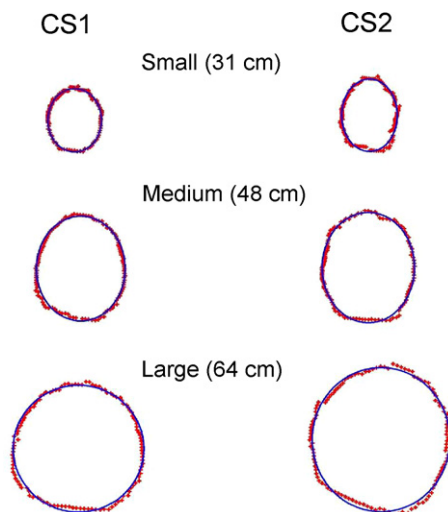


Fig. 5. Examples of digitized CS1 and CS2 with ellipsoids fitted for small, medium, and large cod. Length of the fish is shown in brackets.

Table 2
Estimated regression coefficients for CS1 and CS2.

	Length vs. weight	CS1		CS2	
		Length vs. width	Length vs. height	Length vs. width	Length vs. height
a	2.7×10^{-6}	0.035	0.173	0.032	0.135
b	3.21	1.22	0.99	1.24	1.04
sd (a)	2.3×10^{-7}	0.002	0.007	0.002	0.007
R ²	0.98	0.95	0.97	0.95	0.94

Length, width and height are given in mm while weight is in g. R² represents the ratio of the variance in the data that is explained by the model to the total variance in the data.

28.4 cm for cod from two single hauls collected using a 109 mm diamond mesh codend with 104 open meshes around the circumference. The corresponding estimates of SR were 6.8 and 8.5 cm. Total catch weights in these two hauls were 1500 and 1330 kg, respectively. A 109 mm mesh size measured with an ICES 4 kg wedge would correspond to a 113 mm mesh size when measured with a 5 kg gauge (Ferro and Xu, 1996), as prescribed in legislation. Because the selectivity of diamond meshes predicted by FISHSELECT depends on the mesh opening angle (see Fig. 3), the input values for oa for the meshes used in the simulations need to reflect the experimental fishing conditions. The codend used by Galbraith et al. (1994) was very similar in design to one (mesh size 110 mm, 100 open meshes in circumference) studied by Herrmann et al. (2007b). By applying the finite-element method as described in Priour (2001), Herrmann et al. (2007b) estimated how the average openness of the meshes is influenced by codend catch weight and distance from the edge of the catch in the codend. We used the same information to produce the plot shown in Fig. 4 and to estimate how average oa depends on distance to the edge of the catch and on catch weight. We then used these estimates to obtain realistic values for the range of oa values to input into FISHSELECT to simulate results, which can be compared to those obtained by Galbraith et al. (1994). Fig. 4 clearly shows that the most open meshes occur just in front of the catch edge. Moving forward in the codend, the oa value decreases. At a distance of only 1.5 m from the catch edge, the oa value is largely unaffected by the amount of the catch, whereas at the edge of the catch it is very dependent on the amount of catch. As the catch accumulates during the haul, this phenomenon likely leads to a large within-haul variation of the selection process. It is therefore important to know both where in the codend and when the main escapement of cod takes place.

To obtain a realistic mean distribution of oa for the simulation, we made the following assumption: The final and decisive escape

Table 3
Width and height measurements (mm) of the ellipsoids fitted to CS1 and CS2 (10 repeated measurements conducted on one fish).

	CS1		CS2	
	Width	Height	Width	Height
1	59.00	67.65	64.98	75.85
2	58.44	67.43	65.90	75.21
3	60.67	66.26	64.13	76.54
4	58.42	67.59	65.19	76.23
5	56.46	67.08	64.26	76.95
6	58.48	67.68	66.99	73.06
7	55.71	66.18	65.42	75.67
8	58.26	65.89	65.34	76.20
9	57.36	65.48	65.93	75.22
10	55.91	67.53	66.06	75.28
Mean	57.87	66.88	65.42	75.62
sd	1.53	0.84	0.86	1.07

sd = standard deviation.

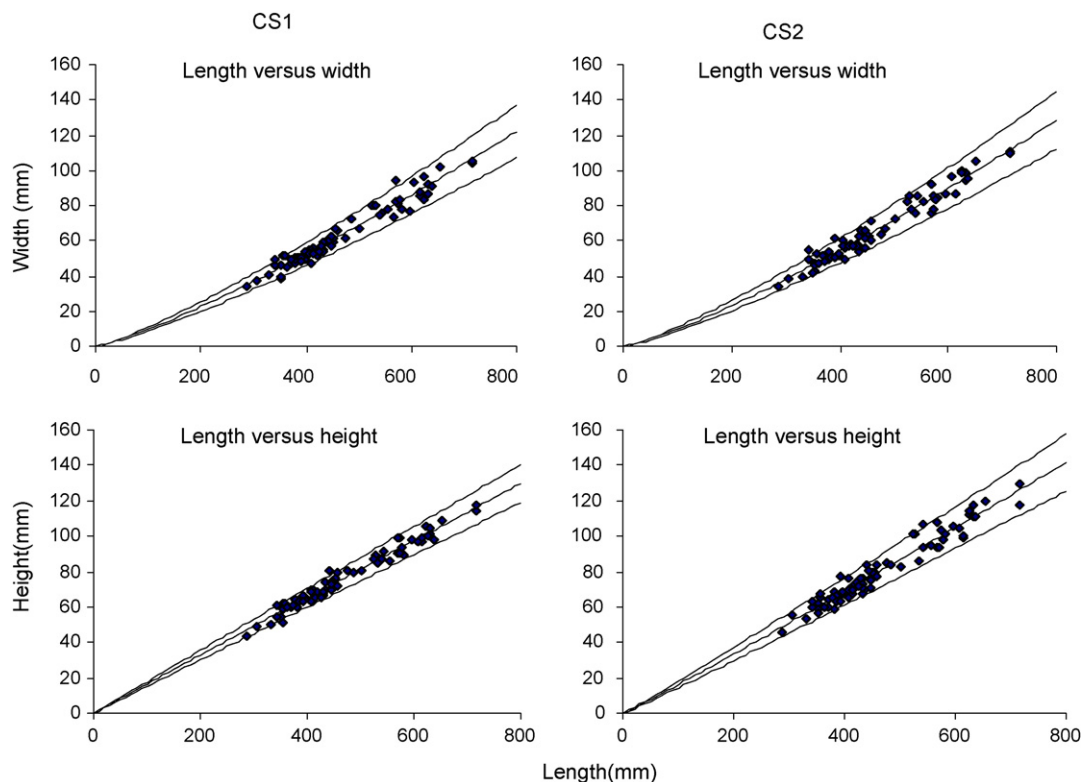


Fig. 6. Length-based regression lines (solid lines) for width and height of the ellipsoids fitted to the cross-section contours for CS1 (left) and CS2 (right). The hatched lines represent the confidence limits (95%) for the simulated variation between individuals in these regressions.

attempts by cod are uniformly distributed throughout the haul in the zone from the edge of the catch and 1.5 m forward in the codend. Using the catch weights presented in Galbraith et al. (1994) at the end of the hauls, the resulting θ values should range from 15° to 65° with a mean value of approximately 35° (Fig. 4). Simulations in FISHSELECT were used to investigate the influence on the selectivity parameters of increasing the range of θ values distributed uniformly around a basepoint of 35° . The best penetration model (see Section 2.8) and the virtual cod population used when producing the design guides were used to predict L50 and SR in the simulations. The results for each θ in the ranges were weighted equally, meaning that the total retention data for the codend could be created by aggregating the retention data for each θ . Retention data were analyzed as described in Section 2.9 to obtain estimates of L50 and SR.

In FISHSELECT we generally assume that the mesh shapes do not deform during fish penetration (i.e., the stiff mesh assumption; see Section 2.6). However, for the sake of completeness and to better evaluate how well the stiff mesh assumption complies with results from experimental fishing, a soft mesh model was implemented in the FISHSELECT software; this model assumes that the mesh shape can be fully distorted by fish that are attempting to pass through it. Thus, the condition for penetration is that the perimeter of the compressed fish cross-section shape does not exceed the perimeter of the mesh ($2 \times$ mesh size). In this model, actual mesh shape does not influence the selective properties. To investigate whether soft mesh penetration is of relevance when simulating experimental trawl fishing, we also attempted to simulate the two Galbraith et al. (1994) hauls described above using the soft mesh model. For this purpose, compression values of cross-section shapes found for the best penetration model for stiff meshes were used to estimate the cross-section shape perimeter for use in the soft mesh model. The same virtual population of cod used previously was used for this simulation.

2.11. Stochastic simulation of between-haul variation of experimental results

The spatial distribution of the fish on the fishing ground likely is not uniform (Greenstreet et al., 1997) and the distribution likely will vary among hauls. Therefore, the filling pattern of the codend will vary from haul to haul. Because the θ in a diamond mesh codend depends both on the amount of catch and on the distance to the catch edge (Fig. 4), groups of fish arriving at different stages during the fishing process will experience different probabilities for mesh penetration that are related to the range of θ present. This mechanism potentially could lead to a between-haul variation in the size selection process. Additional between-haul variation in the range of θ values present might result from codend pulsing caused by differences in sea state (O'Neill et al., 2003). Whether these mechanisms can lead to between-haul variation in the selection parameters that are of the same order of magnitude as those obtained experimentally was investigated by using the stochastic simulation function of the FISHSELECT software that enabled simulation of repeated hauls. As input, this function requires: (1) a list of meshes with different θ values covering the full ranges of mesh shapes present in all hauls, and (2) a description of the total population of fish arriving in the codend (composed of different subpopulations). The relative occurrence of the different meshes in the list was varied randomly within predefined limits between hauls and independently for fish belonging to different subpopulations. For each haul the summed retention data were used to estimate L50 and SR (see Section 2.9).

Dahm et al. (2002) presented selectivity data for 95 mm diamond mesh codends, which correspond to about 99 mm if measured with a 5 kg mesh gauge (Ferro and Xu, 1996). The total catch weight varied from 119 to 1233 kg and results from 43 individual hauls were presented. The stochastic simulation function of FISHS-

ELECT was used to simulate these hauls. We first needed to define a realistic range of oa values present in the codend. Based on the reported catch range and Fig. 4, we selected an oa range of 15–75°, which is larger than the range used to simulate the average selection process in a codend with mesh size of 113 mm. This discrepancy is justified because with the smaller mesh size and the same number of meshes around the codend, meshes will open more with the same amount of catch due to the shorter codend circumference. We are concerned not only with the average oa range but also with the full range, which includes potential increases that could result from codend pulsing in some hauls. A virtual population of cod with an average size structure similar to the population reported in Dahm et al. (2002) was created by summing two virtual subpopulations of cod normally distributed around the two peaks in the size structure. In the simulated hauls, the two subpopulations were treated individually as described above. For each value of oa, the relative occurrence was varied randomly from 0% to 100% to simulate the fact that some values do not appear in some hauls. Three different simulation scenarios were investigated with 20,000 repeated hauls in each: (i) a penetration model based on CS2 uncompressed and an oa range of 15–75°; (ii) the best penetration model and an oa range of 15–75°; and (iii) the best penetration model and an oa range of 25–75°.

3. Results

3.1. Description of cross-section shapes

Fig. 5 shows examples of digitized cross-section shapes with fitted ellipsoids. Length-based regressions for both the width and height of the ellipsoids fitted to CS1 and CS2 are given in Fig. 6. Table 2 lists the regression coefficients. The R^2 values (ratio of the variance in the data explained by the model to the total variance in the data) indicate that the regression models describe the data well. The regression curves for width and height versus fish length indicate that the growth in the cross-section shape is not fully isometric over the measured length span of the fish. The simulated morphological variation is in good agreement with the experimental data (Fig. 6). This morphological variation increases with increasing fish size (Fig. 6).

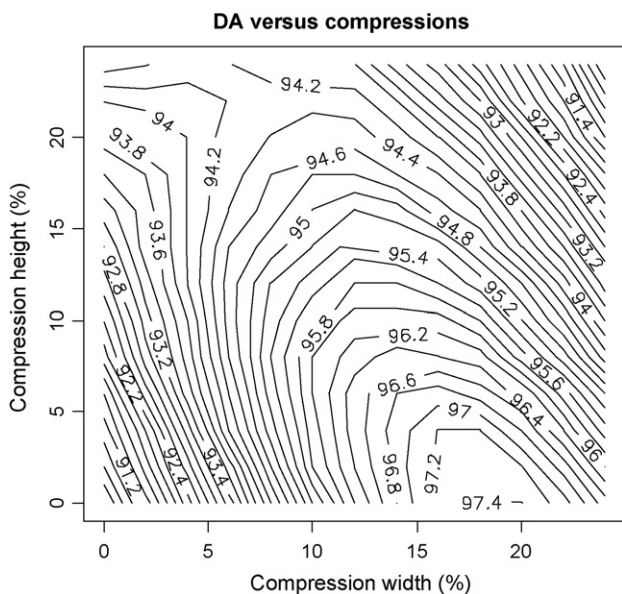


Fig. 7. Iso-DA curves vs. compression of width and height of the ellipsoids fitted to CS1. Points along the 45° angle line from (0, 0) represent symmetrical compression.

3.2. Repeated measures

The parametric shapes fitted to 10 successive cross-section measurements of the same cod varied little in the parameter values. This indicates that the resolution and accuracy of the MorphoMeter measurements are acceptable for measuring the outlines of deformable objects (Table 3). The largest variation occurred for the width of CS1, for which 95% of the measurements were within $\pm 5.2\%$ of the mean value. When the fall-through experiments on two cod were repeated three times, all results for one cod were identical in the three experiments for all 118 mesh templates. The second cod, however, was retained by one mesh template in the second run, whereas it passed through it in both the first and third runs. We considered this difference to be marginal and assumed that the morphological features relevant for mesh penetration were not affected noticeably by the extensive fall-through trials. This assumption is supported by the measurements of the cross-section shapes before and after the trials; deviations were $< 5\%$, which is within the measuring accuracy reported at the beginning of this section.

3.3. Penetration model

Simulation results from a full matrix of asymmetric compression ratio combinations ranging from 0% to 24% with a penetration model considering only CS1 (see Section 2.8) were compared to results from the fall-through trials (see Section 2.6), resulting in a matrix of 169 DA values when using steps of 2%. Iso-DA curves versus compressions in width (x-axis) and height (y-axis) were constructed (Fig. 7). The highest DA value (97.6%) was obtained for CS1 by compressing the height by 0% and the width by 18%. Simulations using a penetration model considering CS2 alone yielded a maximum DA value of 95.7%. Penetration models that considered both CS1 and CS2 also were tested for 312 combinations of various compressions of CS1 and CS2. Both the DA value and the compression value for CS1 in the best combined penetration model were identical to those obtained in the best penetration model considering CS1 alone. This best combined model requires 32% compression of CS2, which makes the compressed dimensions of CS2 smaller than those of CS1. Fig. 8 illustrates the ellipsoids fitted to the measured cross-sections for a typical cod along with compressed shapes used for this best combined penetration model. Based on our results, we conclude that CS2 is of little importance for the selective process of the mesh for cod and, for simplicity, we chose the penetration model that considers CS1 alone. In the following text, this model is referred to as the best penetration model. Another way of expressing the goodness of the best penetration model is to say that there is about 2.4% disagreement between the results from fall-through experiments and the simulated results. Further validation can be provided by investigating the distribution of the scaling factors (sf , see Section 2.7) of the disagreeing results (Fig. 9A). For this penetra-

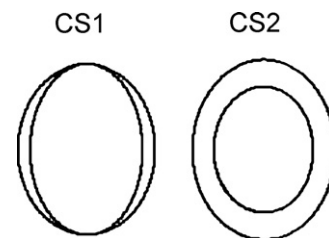


Fig. 8. Ellipsoids (outer ellipsoids) fitted to the measured cross-sections CS1 and CS2 and the ellipsoids (inner ellipsoids) used to represent the compressed cross-sections in the best penetration models (compression the height of CS1 by 0% the width by 18% and a symmetrical compression of CS2 of 30%). CS1 and CS2 are scaled equally and originate from the same fish.

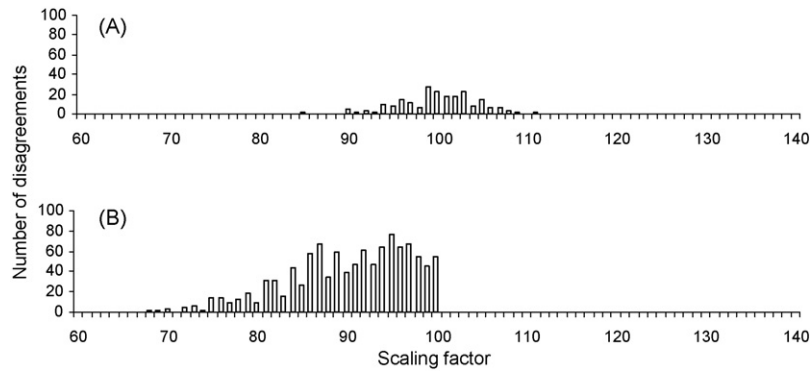


Fig. 9. Distribution of the scaling factor values for disagreeing results when comparing experimental and simulated fall-through results assuming different penetration models. (A) Model based on 18% compression of the width and 0% of the height of CS1 (the selected best penetration model). (B) Model based on CS2 uncompressed.

tion model, they are evenly distributed around 100%, indicating that the penetration model is unbiased. Only 0.5% of the results disagree more than the 95% confidence limits for the measuring accuracy on the cross-section shapes (Section 3.2).

The procedure described above shows that with support from the fall-through experiments, we can estimate the potential compression of the measured cross-section shapes. With the penetration model assuming an uncompressed cross-section approximation of CS2, we would have severely underestimated the length of cod that can penetrate a given mesh. The result of using such a penetration model is illustrated by the distribution of the *sf* values shown in Fig. 9B. The DA value of this penetration model would only be 87.8%, which represents an increase of the disagreement of 500% compared to the best penetration model. The above results demonstrate that the FISHSELECT method is a sensitive tool for detecting how good different approximations used in the penetration models are.

3.4. Design guides

Based on the best penetration model (CS1 alone), design guides were produced as described in Section 2.9 to predict the basic selective properties of the four mesh types investigated for cod

(Figs. 10–12). The figures show that the predicted L50 values depend on the actual mesh shape (i.e., the oa values of diamond and hexagonal meshes and the SFA values in rectangular meshes). Changes in mesh size when oa values or SFA values are low have little effect on the predicted L50 for diamond, rectangular, and hexagonal meshes. The design guides can thus be used to identify the conditions required to obtain a specific and constant selection during a fishing process. Combined with knowledge about the mesh configurations (type, size, and oa range) in a specific codend, they also can indicate the expected range of selection parameters. This range defines the possible within-haul and between-haul variations and thus also what potentially can be obtained by stabilizing mesh shapes (i.e., reducing the range of mesh openings) during the catch build-up process. The estimates for the square meshes that are a special case in all three guides are the same (e.g., a square mesh with a mesh size of 200 mm is assigned an L50 value of approximately 70 cm in all design guides; top right corner in Figs. 10–12).

A maximum L50 value is reached at $oa \approx 75^\circ$ for a diamond mesh (Fig. 10), at $SFA \approx 70\%$ for rectangular meshes (Fig. 11), and at $oa \approx 120^\circ$ for hexagonal meshes (Fig. 12). Due to the non-isometric growth of cod (see Section 3.1 and Figs. 5 and 6), the cross-section

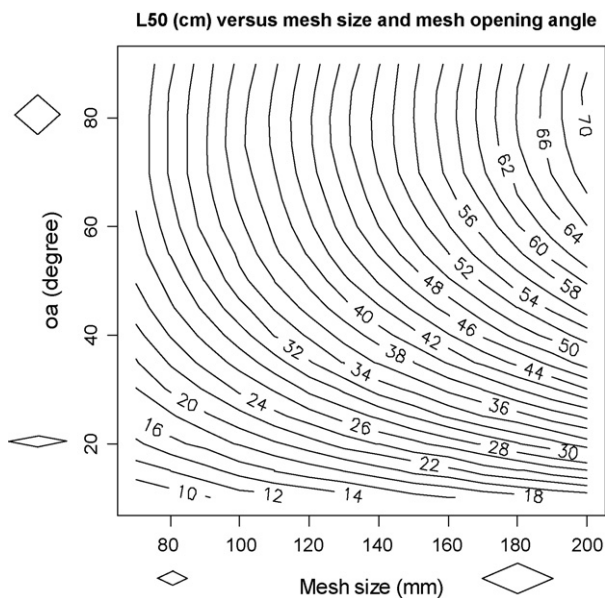


Fig. 10. Diamond mesh design guide showing iso-L50 curves as a function of mesh size (mm) and mesh opening angle (oa; in degrees). The right side of the plot ($oa = 90^\circ$) corresponds to square meshes.

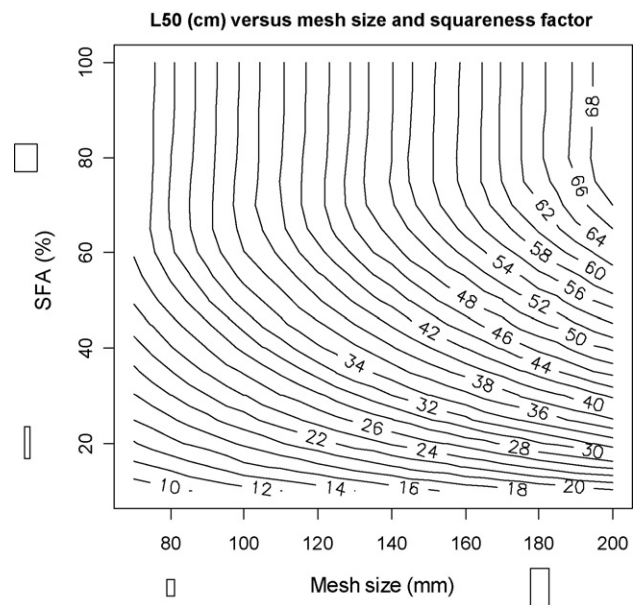


Fig. 11. Rectangular mesh design guide showing iso-L50 curves as a function of mesh size (mm) and squareness factor (SFA; %). The right side of the plot (SFA = 100%) corresponds to square meshes.

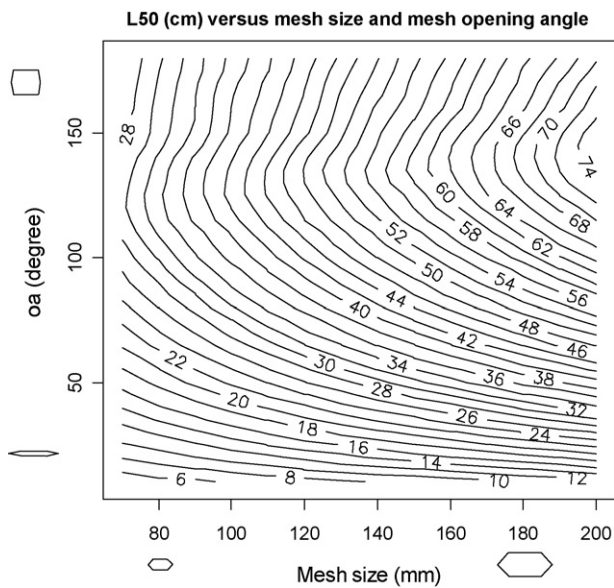


Fig. 12. Hexagonal mesh design guide showing iso-L50 curves as a function of mesh size ($k + 2 \times b$ in Fig. 3) (mm) and mesh opening angle (oa; in degrees). The right side of the plot (oa = 180°) corresponds to square meshes. Only for designs for which $b = 0.5 \times k$.

shape of cod becomes slightly more rounded with increasing fish size, and for larger mesh sizes the maximum L50 value will shift towards higher oa/SFA values.

Fig. 13 shows the uncompressed ellipsoids fitted to CS1 and the corresponding compressed ellipsoids used in the best penetration

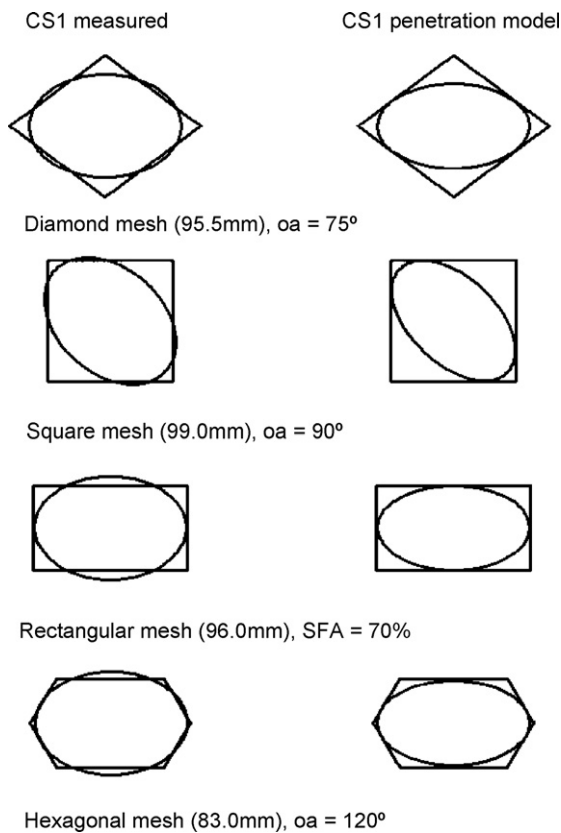


Fig. 13. The optimal mesh configurations for a 36 cm cod, which, according to the best penetration model, will allow it to just pass through (right). The measured ellipsoid of CS1 is shown with the same meshes (left).

Table 4

FISHSELECT predictions of L50 and SR assuming different ranges of opening angles (oa) in a 113 mm codend.

Source	oa range (°)	L50 (cm)	SR (cm)
Galbraith 1		29.2	6.8
Galbraith 2		28.4	8.5
FISHSELECT	35	29.8	1.2
	30–40	29.9	3.0
	25–45	29.6	4.9
	20–50	29.4	7.3
	15–55	29.2	10.0
	15–65	31.7	11.8
	Soft mesh	52.2	1.9

The simulation assumes that the final escape attempts are equally distributed along a part of the codend in front of the catch (see Sections 2.10 and 3.5 for details). Galbraith 1 and 2 refer to results from single tows in Galbraith et al. (1994).

model for the different mesh types, all at optimal oa/SFA. At optimal mesh configuration, the highest L50 value for cod for a given mesh size occurs in hexagonal meshes. The values of the different minimum mesh sizes needed for a 36 cm cod to pass through the mesh are also shown in Fig. 13.

3.5. Results of simulation of within-haul variation of experimental size selection

Different scenarios assuming different mesh oa ranges for a codend with mesh size 113 mm were simulated using the best penetration model (see Section 3.3). Comparison with sea trial results (Section 2.10) was conducted and Table 4 lists the results. If oa were constant (e.g., 35°), SR would depend only on the morphological variation of the virtual cod population. A comparison of this single-oa SR value with the SR values obtained experimentally (Galbraith 1 and 2 in Table 4) shows that the morphological variation only constitutes about 14% and 18% of the SR value obtained in sea trials. With increasing oa range of the meshes SR increases in the simulations. The results in Table 4 (L50, SR versus mesh oa range) show that a realistic prediction of the selectivity parameters can be obtained by simply assuming a reasonably wide range of mesh oa values. A straightforward explanation of the value of SR can thus be provided under the stiff mesh assumption. The stiff mesh assumption is further supported by the unrealistic selection parameter values obtained when applying the soft mesh model (Table 4). Under the soft mesh (see Section 2.10) assumption, neither the number of meshes around the codend circumference nor the mesh oa values in the codend (correlated parameters) would have any effect on codend selection. This result would contradict experimental evidence (Reeves et al., 1992; Galbraith et al., 1994). We therefore conclude that the soft mesh model is of little relevance for explaining the size selection of a diamond mesh trawl codend.

3.6. Results for stochastic simulation of between-haul variation in experimental results

The between-haul variation observed and reported by Dahm et al. (2002) was analyzed in the present study using the stochastic simulation method (see Section 2.11). Dahm et al. (2002) reported L50 values that varied between 22.5 and 35.2 cm. According to the design guide (Fig. 10), the full range of oas (15–75°) (see Section 2.11) would correspond to L50 values between 14 and 37 cm. A value of 37 cm is quite similar to the experimentally determined maximum L50 value of 35.2 cm, whereas the lower L50 value of 14 cm is far below the experimental minimum value (22.5 cm). This may indicate that the place of escapement is not totally random and that the likelihood of a final escape attempt increases closer to the catch edge, where the oa is larger. If we instead used the oa as it is at the

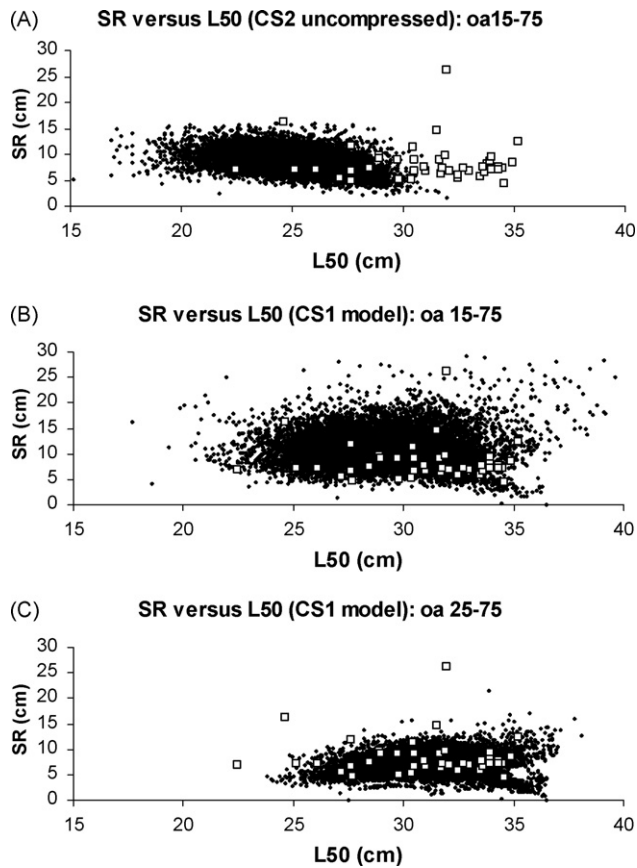


Fig. 14. Comparison between experimental selectivity data presented by Dahm et al. (2002) and stochastic simulations of selectivity data with different models (see Sections 2.11 and 3.6). (□): Single haul experimental results; (◆): single haul simulated results.

catch edge for a small catch as the lower limit ($\approx 28^\circ$ according to Fig. 4), Fig. 10 yields an L50 of ≈ 23 cm, which is close to the observed minimum value.

Next we turn to the results from the 20,000 stochastic simulated hauls for the four scenarios described in Section 2.11. The first scenario (i) used an uncompressed CS2 in the penetration model. The

experimental values of L50 and SR found for single tows in Dahm et al. (2002) were compared to the simulated results (Fig. 14A). This penetration model underestimated the value of L50 considerably compared to the experimental results. A better agreement with experimental data was obtained when the best penetration model (scenario (ii) in Section 2.11) was used (Fig. 14B), and even better agreement occurred when the oa range used to generate the random variation was narrowed from $15-75^\circ$ to $25-75^\circ$ (scenario (iii) in Section 2.11) (Fig. 14C). The exclusion of the least open meshes from the analysis reduced the extent of the possible overall variation in the selection parameters while still generating good agreement with the experimental selection parameters, except for a few outliers. This result further indicates that the occurrence of escapes in front of the catch accumulation in the codend is not a fully random process: The probability is greater that a fish will make its final escape attempt closer to the catch edge (higher oa values) than further ahead of the catch. This complies well with observations reported in Stewart and Robertson (1985).

3.7. Explorative simulation of between- and within-haul variation

In the previous section we showed that stochastic simulation using scenario (iii) led to results (Fig. 14C) that mainly agreed with those observed experimentally in sea trials. This was based on the scenario for an oa range of $25-75^\circ$. Fig. 15 plots the simulated results (the bold curve) showing between-haul distributions of L50 and SR. The vertical bars represent mean results from Dahm et al.'s (2002) two cruises. Both of the experimentally obtained results agree well with the simulated distributions for both L50 and SR. Assuming that this scenario simulates the experimental situation well, we can use it to predict the consequences of altering the range of oa and thus the possible gain of decreasing variability of actual mesh shapes in a codend. Simulated results for high oa values that lie within a narrower range indicate that altering the oa range may be an efficient way to reduce both between- and within-haul variation in the selection process. Fig. 15 shows this effect (i.e., the results of using the stochastic simulation process described in Section 2.11, but with three different narrower ranges for oa). If the oa range is narrowed down to $55-75^\circ$ (Fig. 15, dotted curve), all cod that enter the codend will meet rather similar escape conditions. The result is a smaller between-haul variation of both L50 and SR, a higher mean L50, and a lower mean SR.

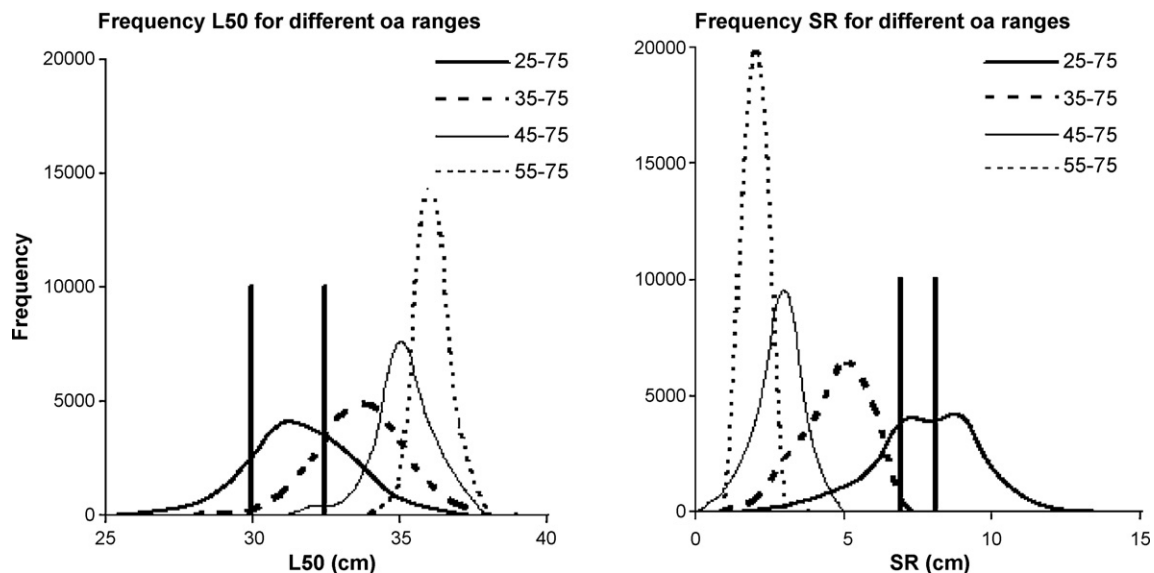


Fig. 15. Explorative simulation of distributions for L50 and SR assuming different ranges for oa (see Sections 2.11 and 3.7 for details).

4. Discussion

Using FISHSELECT methodology, tools, and software, we defined and measured the morphological cross-section shapes that limit the ability of cod to penetrate different mesh configurations. Based on CS1 measurements, a penetration model was established that explains 97.6% of the results obtained during the fall-through experiments. The high DA indicates that the morphological features that are important for cod to pass through meshes are well defined by the penetration model. The less explanatory penetration models, such as those based on criteria using the larger CS2 compressed (DA = 95.7%) or uncompressed (DA = 87.8%), demonstrate that a maximum cross-section measure (i.e., the girth measurement) is inadequate. In static gear like trammel nets or gill nets, where the low mesh bar tension and the thin twine make the mesh more flexible, the girth measure may be more relevant than in towed gear. The large difference between the L50 and SR estimates obtained with the stiff mesh model and the soft mesh model indicates that the morphological conditions for mesh penetration are quite different in towed gear and in static fishing nets. The comparison of sea trial results with theoretical results obtained with FISHSELECT is used to validate the methodology and illustrate that we were able to provide an explanation for both within- and between-haul variation in selection parameters for cod.

For a given mesh size, the highest L50 values for cod were obtained with mesh configurations that most closely resemble the shape contour of CS1 when it is compressed, according to the best penetration model. In general, this is the case for the more open meshes, but among the stiff meshes tested, especially the hexagonal mesh, results in high L50 values. The L50 values depend on the oa of the meshes, especially for the diamond type. The strong dependency between the selection parameters and the value of oa, as shown in the design guides, means that the variation of oa during the fishing process is the primary source of variation in the L50 values predicted in the simulations. The variation is highest in the early stages of the catch build-up process and smaller later on when the maximum perimeter of the codend is reached. All hauls will go through these highly variable stages unless the oa in the codend meshes can be controlled. Such control would allow equal and optimal selective opportunities for all cod entering the codend and would reduce SR. This would reduce considerably both the within-haul and between-haul variation of the selection process. These results are similar to those obtained for haddock by Herrmann and O'Neill (2005).

Isaksen and Valdemarsen (1990) reported that shortening the selvage ropes increased the oa values in diamond mesh codends and increased L50 compared to a standard codend. Other mechanisms that remove the initial stretching tension from the codend netting are likely to have similar effects because they avoid the small oa values. A simple method for increasing the mean oa during a haul is to reduce the number of diamond meshes in the circumference. This makes the selection process more stable at lower catch weights because the maximum codend perimeter is reached earlier in the fishing process (Herrmann et al., 2007b). Experiments with alternatives to diamond mesh, such as square mesh, in codends have resulted in narrower selection ranges (SR) for cod and haddock (*Melanogrammus aeglefinus*) (Robertson and Stewart, 1988; Halliday et al., 1999; He, 2007). This may be related to the fact that square meshes stay more open than diamond meshes during fishing (Robertson and Stewart, 1988; He, 2007).

The estimates of the oa values for the diamond mesh codend used in this study were based on calculations for gear when it is towed along the seabed. The haul-back process and its possible influence on the mean oa values were not taken in account.

However, experimental data have shown no significant statistical difference in L50 for whiting (*Merlangius merlangus*) and haddock among the period of towing along the seabed, the haul-back period, and the short period when the trawl is at the surface (Madsen et al., 2008).

The escape of fish along the netting in front of the catch edge probably is not distributed evenly. Our simulations agree better with experimental data when we assume that the escapes increase towards the catch edge, which supports prior findings reported in Stewart and Robertson (1985).

In our model, the force that the fish can produce during an attempt to penetrate a mesh is set to be equivalent to the force of gravity. Whether this assumption is realistic is unknown and lacks validation. The rationale behind the assumption is that the force of gravity increase with the weight of the fish. This complies well with the assumption that the force a fish can provide during mesh penetration increases with the size of the fish (Efanov et al., 1987). Comparison with experimental results indicates that this assumption leads to reasonable results.

The present experiments were conducted in February during the spawning season of cod. The batch of cod examined contained some larger fish with well-developed gonads, which may have affected the measured dimensions of CS2. However, even for those fish, the degree of compression used for CS2 in the penetration model reduced its dimensions to less than those of CS1 supporting that the best penetration model based on CS1 would provide reasonable results during all seasons.

The information given in the design guides will allow gear designers and managers to get a quick overview of the basic theoretical selectivity of different netting designs or escape panels and the potential improvements that can be obtained by controlling the oa or SFA values of the meshes. Gear designs can be optimized theoretically with relatively low cost by applying the FISHSELECT methodology before they are tested in expensive sea trials. It is, however, important that gear designs are tested at sea before design parameters are fixed by (e.g., introduction into the legislation), because gear selectivity also is affected by parameters such as fish behavior, vessel size, and sea state (Wileman et al., 1996). Morphologically based simulations also may help gear designers and managers to explore and better understand the mechanisms acting during selection trials. The morphological data collected and the mesh penetration models developed during this study can be integrated into the individual-based predictive codend selection model PRESEMO (Herrmann, 2005a,b). So far, PRESEMO has only been applied to predict different aspects of size selection for a few species of round fish in diamond mesh cod-ends (Herrmann, 2005c; Herrmann and O'Neill, 2005, 2006; Herrmann et al., 2006, 2007a,b; O'Neill and Herrmann, 2007; Sala et al., 2006). An important reason for its limited use has been the lack of morphological data relevant to mesh penetration for other, important species. Use of the methodology described in this paper will provide this information and also identify the most suitable models for implementing the morphological condition for mesh penetration for other types of mesh shapes and for new species. It could thereby form the basis for extending the predictive power of PRESEMO.

We have presented and demonstrated the use of the FISHSELECT methodology and its potential for studying size selection of round fish in towed gear. We expect that this methodology will be able to provide useful information on size selectivity of flatfish but, due to the differences in morphology, the cross-section shapes and penetration models likely will be very different from those found for cod. Providing design guides for more of the species that traditionally are caught in the same fisheries will allow quantitative multi-species considerations, where the consequences for each catch component can be estimated for different design strategies.

Acknowledgements

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Appendix A. Generic condition for mesh penetration

This appendix outlines the generic condition implemented in the FISHSELECT software to evaluate whether a fish cross-section shape described by an outside curvature in polar coordinates (Ψ , rf) can pass through a mesh described by an inside curvature (θ , rm), also in polar coordinates. Fig. 16 illustrates this situation. The description of the fish curvature is in a local coordinate system (xf , yf), whereas the mesh curvature is described relative to the coordinate system (xm , ym). The transformation from system (xf , yf) to system (xm , ym) is conducted by rotation Φ followed by translations tx and ty . As shown in Fig. 16, the condition that allows the fish cross-section shape curvature to pass through inside the mesh curvature can be expressed as: $rm(\theta) - rfm(\theta) \geq 0$ for all angles from 0° to 360° , where rfm is the fish curvature expressed in the coordinate system (xm , ym). Thus, the magnitude of rfm will be a function of Φ , tx , ty , and $rf(\Psi)$ for each angle θ , or $rfm(\theta, rf(\Psi), \Phi, tx, ty)$. We can investigate whether penetration is possible by means of a minimization condition. Penetration is possible if:

$$\begin{aligned} \min(\text{merit}(\Phi, tx, ty)) &= 0 \\ \text{where} \\ \text{merit}(\Phi, tx, ty) &= \frac{1}{n} \sum_{i=1}^n dm(\theta_i, \Phi, tx, ty) \\ \text{where} \\ dm(\theta, \Phi, tx, ty) &= \begin{cases} 0 & \forall \quad rm(\theta) - rfm(\theta, rf(\Psi), \Phi, tx, ty) \geq 0 \\ (rfm(\theta, rf(\Psi), \Phi, tx, ty) - rm(\theta)) & \forall \quad rm(\theta) - rfm(\theta, rf(\Psi), \Phi, tx, ty) < 0 \end{cases} \end{aligned} \quad (1)$$

The summation is conducted over n discrete angles θ_i between 0° and 360° .

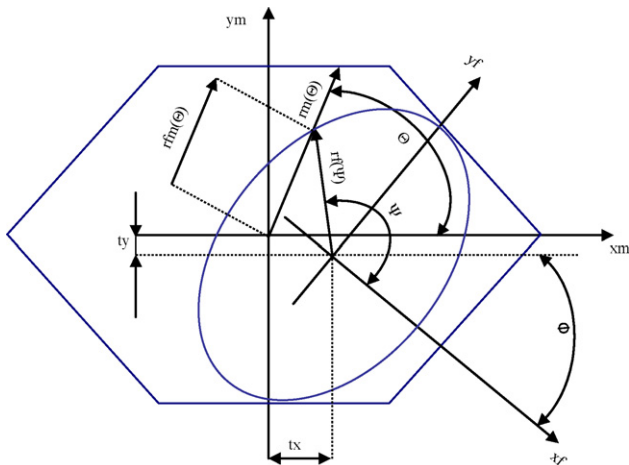


Fig. 16. Outline of the penetration condition. $rm(\theta)$ represents the mesh curvature relative to coordinate system (xm , ym), and $rf(\Psi)$ represents the fish cross-section curvature relative to coordinate system (xf , yf). $rfm(\theta)$ represents the fish curvature transformed to be relative to the (xm , ym) coordinate system. Rotation Φ followed by translations tx and ty transforms the description from the (xf , yf) coordinate system to the (xm , ym) coordinate system.

Penetration is possible if there is at least one set of values (Φ , tx , ty) where $\text{merit}(\Phi, tx, ty) = 0$.

In addition to letting the simulation procedure predict whether or not the penetration condition given by (1) is fulfilled for a particular fish cross-section shape, we also want to know how close the condition was from being just fulfilled. To do this we introduce a scaling factor, sf , to scale the fish cross-section shape up ($sf > 100$) or down ($sf < 100$) isomorphically:

$$srfm(\theta_i) = \frac{sf \times rfm(\theta_i)}{100} \quad \text{for } i \in [1; n] \quad (2)$$

By varying sf and substituting rfm with $srfm$ in (1), we can find the maximum value of sf for which (1) is just fulfilled:

$$\max(sf) \quad \text{while} \quad \min(\text{merit}(\Phi, tx, ty)) = 0 \quad (3)$$

If $\max(sf)$ is < 100 , then the fish cross-section shape is not able to pass through the mesh and the value of $\max(sf)$ quantifies how far condition (1) is from being fulfilled. If $\max(sf)$ is > 100 , the fish cross-section shape is able to pass through the mesh and the value of $\max(sf)$ quantifies how far condition (1) is from being not fulfilled.

Formulas (1)–(3) are generic expressions used to determine whether a fish cross-section shape is geometrically able to pass through a mesh. They are independent of the specific shapes of the mesh and of the cross-section of the fish. To analyse a specific situation we have to define $rm(\theta)$ and $rf(\Psi)$ for θ and Ψ in the interval 0 – 360° . Parametric descriptions for diamond, square, rectangle, and hexagonal meshes have been implemented in the FISHSELECT software to describe the mesh shapes (see Fig. 3). For description of cross-section shapes of cod and other round fish, an ellipsoid shape was used.

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Paper 3



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Selective haddock (*Melanogrammus aeglefinus*) trawling – avoiding cod (*Gadus morhua*) bycatch.

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Selective haddock (*Melanogrammus aeglefinus*) trawling: Avoiding cod (*Gadus morhua*) bycatch

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Abstract

The critical condition of the North Sea cod stocks has resulted in restrictions on not only cod but also on haddock and other species that are caught together with cod. Thus, full exploitation of the haddock stock is not possible unless cod can be excluded from the haddock catch. We designed a selective trawl based on the behavioral differences between haddock and cod as they enter a trawl i.e., cod stay close to the seabed whereas haddock rise above it. The trawl's fishing line is raised ~60 cm above the seabed to allow cod to escape beneath the trawl while haddock are retained. To collect the escapees, three sampling bags were attached beneath the raised fishing line. The selective haddock trawl reduced the total catch of cod by 55% during the day and 82% at night, and 99% of the marketable haddock was caught during the day and 89% at night. Cod escape rates were highly length dependent: Smaller cod escaped the trawl in larger numbers than did larger individuals. Whiting, saithe, lemon sole, and plaice also were observed and were included in the analysis.

Keywords: Haddock, *Melanogrammus aeglefinus*, Cod, Species selectivity, Species separation, Fish behaviour, Trawl

1. Introduction

The majority of towed fishing today occurs in a multispecies setting, where to a large extent the trawl catch reflects the species composition present in the trawl's path. In general, these

multispecies fisheries are not able to adjust their catch composition to stock fluctuations and other management concerns. Thus, the protection of one species in a multispecies fishery can affect the exploitation of other species and reduce the total cost efficiency of the given fishery.

In recent years, North Sea cod (*Gadus morhua*) stocks have been at a critical level, in contrast to the species such as haddock (*Melanogrammus aeglefinus*), which today is classified as having full reproductive capacity and is being harvested sustainably (ICES, 2008). Since 2000, the North Sea cod stock has been in such a bad state that ICES advised the closure of all fisheries in which cod is caught (ICES, 2002). At the same time, the North Sea haddock stock was at its highest level in 30 years. Nonetheless, because haddock is taken mostly with cod, ICES advised that “Unless ways to harvest haddock without by-catch or discard of cod can be demonstrated fishing for haddock should not be permitted” (ICES, 2002). Thus, a strong biological and economic incentive exists to solve this classic mixed species fishery problem: How can we restrict fishing on cod without restricting fishing on haddock taken in the same fishery?

Mechanical sorting of haddock and cod based on size is difficult due to the morphological similarities between the two species. Caddy and Agnew (2003) suggested that restoring both the age structure of the population and the stock biomass is an appropriate approach to rebuilding groundfish (e.g., cod) stocks; they warned that focusing solely on improving juvenile survival through a supplementary mesh size increase or using minimum sizes in a recovery plan based on quotas might increase the pressure on the few remaining large and fertile spawners.

Using behavioral differences among species is another approach to addressing this problem. Species-specific behavioral differences exist between cod and haddock as they enter the trawl mouth: Haddock rise from the seabed whereas cod maintain a position close to the seabed (Main and Sangster, 1981). Their follow-up study reported that the best separation of cod and haddock occurred when the separator panel was placed 75 cm over the seabed (Main and Sangster, 1982). Several other studies have tried to utilize this behavioral difference to separate cod and haddock and other species in demersal trawls (Main and Sangster, 1985; Galbraith and Main, 1989; Engås et al., 1998; Ferro et al., 2007). These trials demonstrated an effective separation by which the majority of haddock enters the top compartment and the majority of cod enters the lower compartment. In the North Sea demersal fisheries several other species, such as plaice (*Pleuronectes platessa*), lemon sole (*Microstomus kitt*), dab (*Limanda limanda*), witch (*Glyptocephalus cynoglossus*), monkfish (*Lophius piscatorius*), rays (*Raja* spp.), and *Nephrops* (*Nephrops norvegicus*), enter the lower part of the trawl along with cod (Main and Sangster, 1982; 1985; Ferro et al., 2007). This diverse group

of species represents very different sizes, morphological shapes, and minimum landing sizes (MLS), and the species therefore are difficult to separate mechanically from cod based on size.

This study describes the development and commercial testing of a selective haddock trawl in which the fishing line is raised above the seabed. Fish and other marine organisms that pass beneath the raised fishing line escape the trawl (in contrast to separator trawls designs) with a minimum of contact with the fishing gear. During the experiment, we used small mesh collecting bags to quantify the escapement of fish beneath the raised fishing line. The consistency in the vertical separation of haddock and cod over length and between day and night was estimated. We also evaluated the gear design's commercial applicability to reduce the catch of cod in the haddock fishery.

2. Materials and methods

2.1 Flume tank experiments

Danish fishermen in the North Sea and Skagerrak typically target haddock with a high opening two-panel modified version of a Scottish haddock trawl known in Denmark as a Jackson trawl. Thus, this trawl (with 750 meshes in the fishing circle) was selected for this study and a 1:8 scale model was built and tested in the Hirtshals flume tank (Fig. 1). The fishing line was raised to the equivalent of 75 cm by a large daleno bobbin. Three collecting bags were made following the design described in Ingolfsson and Jørgensen (2006) to quantify the escapement beneath the raised fishing line. The headline height of the trawl was equal to 8 m and the spread of the upper wing to 22 m and of the lower wing to 20 m; towing speed was equal to three knots. The total width of the three collecting bags equaled about 15 m (i.e., the width of each bag, perpendicular to the towing direction, was about 5 m). A float equivalent to a 20 cm float was attached to each of the three collecting bag codends to keep them off of the bottom.

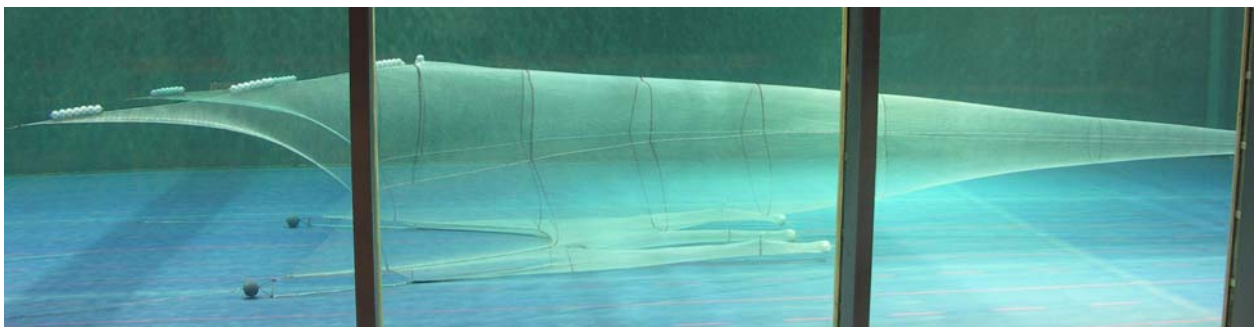


Fig. 1. Model (scale = 1: 8) of the selective haddock trawl in the Hirtshals flume tank. Note the three lower collecting bags.

2.2 Commercial testing

A full-scale experimental trawl was built according to the scale model. The collecting bags and the main codend were constructed of a non-selective 40 mm mesh size (full mesh) made with 1.4 mm nylon twine. Before the sea trials, a row of 20 meshes from each codend was measured with an ICES spring-loaded mesh gauge set at 4 kg. The ground gear was made of 18 cm rock hopper discs in the centre section and 13 cm rock hopper discs in the wing sections, both with 30 cm intervals in between them. In the fisheries, heavy rock hopper gear with about 50 cm discs normally is used. The smaller rock hopper discs used in this study were chosen to minimize the escapement of fish beneath the trawl. It is assumed that all fish in the path of the trawl are caught; however, fishing with small discs restricts fishing to areas with a relatively smooth bottom compared to the grounds that can be fished with heavy rock hopper gear. A 53 cm bunt bobbin was connected to an 80 cm butterfly by a crowfoot made of 19 mm chain (8.5 kg/m). The false fishing line was made of a 19 mm chain (8.5 kg/m), and the raised fishing line was made of a 13 mm chain (3.8 kg/m). The trawl was rigged with 163 m sweeps and 55 m bridles and was spread with a set of 282 cm Thyborøn V doors. The sea trials were conducted onboard the commercial vessel HM 128 *Borkumrif* (28 m and 728 kW) from 7–17 October 2006. The fishing grounds used in this study are located in the southwestern part of the Skagerrak along *Jyske rev* (ICES area 44).

2.3 Catch measurement

Fourteen successful tows were made both during the day and at night. Day tows were conducted from an hour after sunrise to an hour before sunset, and the night tows were conducted between an hour after sunset to and hour before sunrise. The towing time was 30 min at about 3 knots; the short towing time was due to the high density of fish and the small mesh size used in both the collecting bags and in the main codend. Haddock, cod, whiting, saithe, plaice, and lemon sole were collected and measured. In some hauls, haddock, whiting, and saithe were subsampled due to large catches in the main codend. A representative sample was taken by measuring 2–3 30 l baskets of whiting, 8–10 baskets of haddock, and 12–15 baskets of saithe. These numbers of baskets correspond to about 500 fish measured per species in each tow when subsampling was conducted. The weight from the subsample and the total catch of the respective species were determined and a raising factor was estimated. The total catch of cod, plaice, and lemon sole was measured in all hauls. All fish were measured, rounded down to the nearest cm below and 0.5 cm was added in the subsequent analysis.

2.4 Data analysis

Data for haddock, cod, and whiting were included in the model because these species were caught in sufficient numbers throughout the experiment. The data are categorical, with response categories represented by the four compartments from which the fish that entered the gear were finally collected. Furthermore, the sampling scheme forms a cluster structure, with cluster units represented by the hauls in which the gear was tested. This naturally leads to a generalized linear mixed model. We fit the model in a two-stage framework well known from several selectivity studies (e.g., Madsen et al., 1999; Revill and Holst, 2004). The first stage summarizes data from individual hauls into maximum likelihood estimates that are assumed to be approximately multivariate normal. This stage typically employs some variant of the SELECT model (Millar, 1992) that has been adapted to model the specific experiment in question. The second stage uses Fryer's model of between-haul variation (Fryer, 1991). This stage is well described elsewhere, thus here we concentrate on issues specific to this application. First we describe the fixed effects model applicable to a single haul. We then extend the model to cover random effects.

In the following we consider a single haul and therefore omit references to the haul identifier. The catch of length l fish in compartment MC (main codend), S (*starboard*), M (middle), and P (port) are denoted $n_{MC,l}, n_{S,l}, n_{M,l}$, and $n_{P,l}$, respectively. The conditional distribution of the catch of length l fish in the four compartments, given the total catch, is a multinomial:

$$(n_{MC,l}, n_{S,l}, n_{M,l}, n_{P,l} | n_{+,l}) \sim m(n_{+,l}; \pi_{MC,l}, \pi_{S,l}, \pi_{M,l}, \pi_{P,l}),$$

where $n_{+,l} = n_{MC,l} + n_{S,l} + n_{M,l} + n_{P,l}$ and the $\pi_{*,l}$'s are the probability parameters. Because we were interested in both the vertical and the horizontal distributions among the compartments, a baseline logit model using the LM compartment as the baseline category was considered appropriate. For ease of exposition, we assume the probabilities depend only on the length of the fish and are thus given by:

$$\pi_{C,l} = \begin{cases} \frac{\exp(\eta_{C,l})}{1 + \exp(\eta_{MC,l}) + \exp(\eta_{S,l}) + \exp(\eta_{P,l})} & \text{for } C = MC, S, P \\ \frac{1}{1 + \exp(\eta_{MC,l}) + \exp(\eta_{S,l}) + \exp(\eta_{P,l})} & \text{for } C = M \end{cases},$$

where $\eta_{Cl} = \beta_{C0} + \beta_{C1}l$ and $C = MC, S, P$. The β parameters are best interpreted by looking at the probabilities on a logit scale. For example, $\text{logit}(\pi_{MC1}) = \log\left(\frac{\pi_{MC1}}{\pi_{M1}}\right) = \beta_{MC0} + \beta_{MC1}l$ means that β_{MC1} gives the increase in log-odds by one unit increase in length l of being caught in the upper compartment (U) versus being caught in the baseline compartment (M).

The model is readily extended to include other covariates (fixed effects) as well as random effects to account for latent variables associated with the hauls. The general expression for the linear predictor for a length l fish caught in compartment C during haul h is $\eta_{hCl} = \mathbf{x}_{hl}^T \boldsymbol{\beta}_C + \mathbf{z}_{hl}^T \mathbf{b}_{hC}$, where \mathbf{x}_{hl} and \mathbf{z}_{hl} are column vectors of fixed and random covariates respectively and the $\boldsymbol{\beta}_C$ s are the parameter vectors of interest. Finally, we assume that the \mathbf{b}_{hC} s are independent multivariate normals $\mathbf{b}_{hC} \sim \text{MVN}(\mathbf{0}, \mathbf{D})$.

The model described above is fairly general and may be fitted by various tools. In a two-stage approach, the "multinom" procedure in the R package "nnet" can be used for fitting the model for individual hauls. The second stage can be fitted using the ECWEB software (<http://www.constat.dk/ecwebsd/>).

3. Results

3.1 Sea trials

There the chain in the raised fishing lines was shining during the first two test tows, indicating that the fishing line was not raised above the seabed. This premise was supported by very little catch in the three collecting bags, in contrast to the large catches of fish in the main codend and the presence of benthic species such as sea stars and sea urchins in the main codend. Therefore, four 28 cm and eight 20 cm floats were attached to the raised fishing line. Drop chains were placed in the centre of the middle collecting bag to estimate the height of the raised fishing line based on shine. Based on shine from the drop chain, the additional floats raised the fishing line about 60–70 cm above the seafloor and opened the three lower collecting bags. Benthic invertebrate species such as sea stars were thereafter caught only in the three lower collecting bags. Average mesh sizes of the four compartments were 42.51 mm with a standard deviation of 1.10 mm. The trawl geometry used during the 28 valid tows was stable in terms of headline height and door-spread (Table 1).

Table 1. Operational conditions and gear performance.

	Depth (m)	Door spread (m)	Headline height (m)	Speed (knt)	Wind (m/sec)
Average	94.77 ± 10.1	123.5 ± 6.28	8.04 ± 0.2	3.16 ± 0.1	5.21 ± 3.0
Min – Max	77 – 111	104 – 139	7.1 – 9.0	3.0 – 3.3	1.0 – 12.0

3.2 Vertical species separation

Relatively high and consistent catch rates were obtained for haddock, cod, and whiting throughout the experiment (Table 2). Therefore, these three species were included in the statistical modeling. The middle compartment was used in the modeling as the baseline for comparison with the other compartments (starboard, port, and main codends). Saithe, plaice, and lemon sole were also caught but in fewer hauls and in lower numbers (Table 2).

Table 2. Proportions of the total catches in the main codend and the three lower collecting bags. The different species MLS's are: haddock (HAD) = 30 cm, cod (COD) = 35 cm, whiting (WHG) = 23 cm, saithe (POK) = 35 cm, lemon sole (LEM) = 26 cm and plaice (PLE) = 27 cm.

Collecting bag		No. Total	Day tows (%)		No. Total	Night tows (%)			
			No. Total	No. <MLS		No. >MLS	No. Total	No. <MLS	No. >MLS
<u>Port</u>	HAD	131	0.33	0.65	0.03	678	2.70	3.94	2.45
	COD	493	9.81	10.31	6.57	455	15.95	16.61	11.72
	WHG	151	3.43	5.13	2.93	154	4.56	5.92	4.50
	POK	0	0.00	0.00	0.00	37	0.98	7.14	0.92
	LEM	14	11.57	12.50	10.20	2	7.41	5.56	11.11
	PLE	11	25.00	0.00	25.00	1	25.00	0.00	25.00
<u>Middle</u>	HAD	2344	5.99	11.32	0.86	2095	8.35	17.38	6.55
	COD	1666	33.14	36.47	11.49	1326	46.49	48.34	34.64
	WHG	888	20.17	36.82	15.31	550	16.30	31.58	15.58
	POK	1	0.19	0.00	0.20	66	1.76	21.43	1.53
	LEM	53	43.80	54.17	28.57	12	44.44	50.00	33.33
	PLE	18	40.91	0.00	40.91	0	0.00	0.00	0.00
<u>Starboard</u>	HAD	204	0.52	0.98	0.08	534	2.13	3.06	1.94
	COD	647	12.87	14.05	5.22	567	19.88	19.85	20.05
	WHG	136	3.09	5.84	2.29	132	3.91	4.61	3.88
	POK	0	0.00	0.0	0.0	9	0.24	2.38	0.22
	LEM	11	9.09	12.50	4.08	4	14.81	16.67	11.11
	PLE	7	15.91	0.00	15.91	2	50.00	0.00	50.00
<u>Main codend</u>	HAD	36446	93.15	87.04	99.04	21776	86.82	75.62	89.06
	COD	2221	44.18	39.18	76.72	504	17.67	15.19	33.59
	WHG	3228	73.31	52.21	79.47	2539	75.23	57.89	76.05
	POK	512	99.81	100.00	99.80	3645	97.02	69.05	97.34
	LEM	43	35.54	20.83	57.14	9	33.33	27.78	44.44
	PLE	8	18.18	0.00	18.18	1	25.00	0.00	25.00

In general, among all species caught regardless of day or night, the majority of a particular species always entered either above or beneath the raised fishing line. During the day 93% of the haddock (total numbers) and 99% of marketable haddock (above MLS) were caught in the main codend (Table 2); at night the values for the main codend catch were 87% and 89%, respectively. During the day, 44% of cod (total numbers) and 77% of marketable cod (above MLS) were caught in the main codend; at night the values were 15% and 34%, respectively (Table 2). The separation of cod, haddock, and whiting into the lower compartments beneath the raised fishing line was significantly higher ($P < 0.001$) at night than during the day (Table 3). The separation into the main codend was in general reduced during the night tows for cod, haddock, and whiting.

Table 3. Significant effects for haddock, cod, and whiting using the middle compartment as a baseline for the statistical comparisons between compartments. Day was used as the baseline for day/night comparisons.

Species	Parameters		Estimate (S.E)	df	P
	Compartment	Effect			
Haddock	Port	Intercept	-2.62 (0.39)	160	<0.001
	Main	Intercept	-2.31 (0.33)	160	<0.001
	Starboard	Intercept:Length	-0.18 (0.06)	160	0.001
	Main	Intercept:Length	0.2 (0.01)	160	<0.001
	Starboard	Night	-3.3 (1.06)	160	0.002
	Main	Night	1.55 (0.51)	160	0.003
	Starboard	Night:Length	0.24 (0.09)	160	0.006
	Main	Night:Length	-0.11 (0.02)	160	<0.001
Cod	Starboard	Intercept	-0.93 (0.19)	163	<0.001
	Port	Intercept	-1.3 (0.27)	163	<0.001
	Main	Intercept	-3.01 (0.34)	163	<0.001
	Main	Intercept:Length	0.11 (0.01)	163	<0.001
	Main	Night	-1.24 (0.36)	163	<0.001
Whiting	Main	Intercept	-7.48 (1.11)	168	<0.001
	Main	Intercept:Length	0.32 (0.05)	168	<0.001
	Starboard	Night	-3.34 (1.05)	168	0.002
	Port	Night	-2.51 (1.02)	168	0.015
	Main	Night	4.78 (1.6)	168	0.003
	Main	Night:Length	-0.15 (0.06)	168	0.023

The vertical separation between the lower middle compartments in the centre of the ground gear and the main codend was significantly different ($P < 0.001$) for haddock, cod, and whiting (Table 3). The length dependency of the vertical separation was significantly different ($P < 0.05$) between day and night for haddock, cod, and whiting (Table 3). A larger proportion of the smaller individuals were caught in the lower compartments at night compared to during the day (Fig. 2 and

3). The vertical separations estimated confidence bands (95%) for the day tows compared to the night tows are narrower, which indicates a higher haul-to-haul variation during the night tows (Fig. 3). Furthermore, the slope of the estimated vertical separation for haddock, cod, and whiting was steeper during the day than at night.

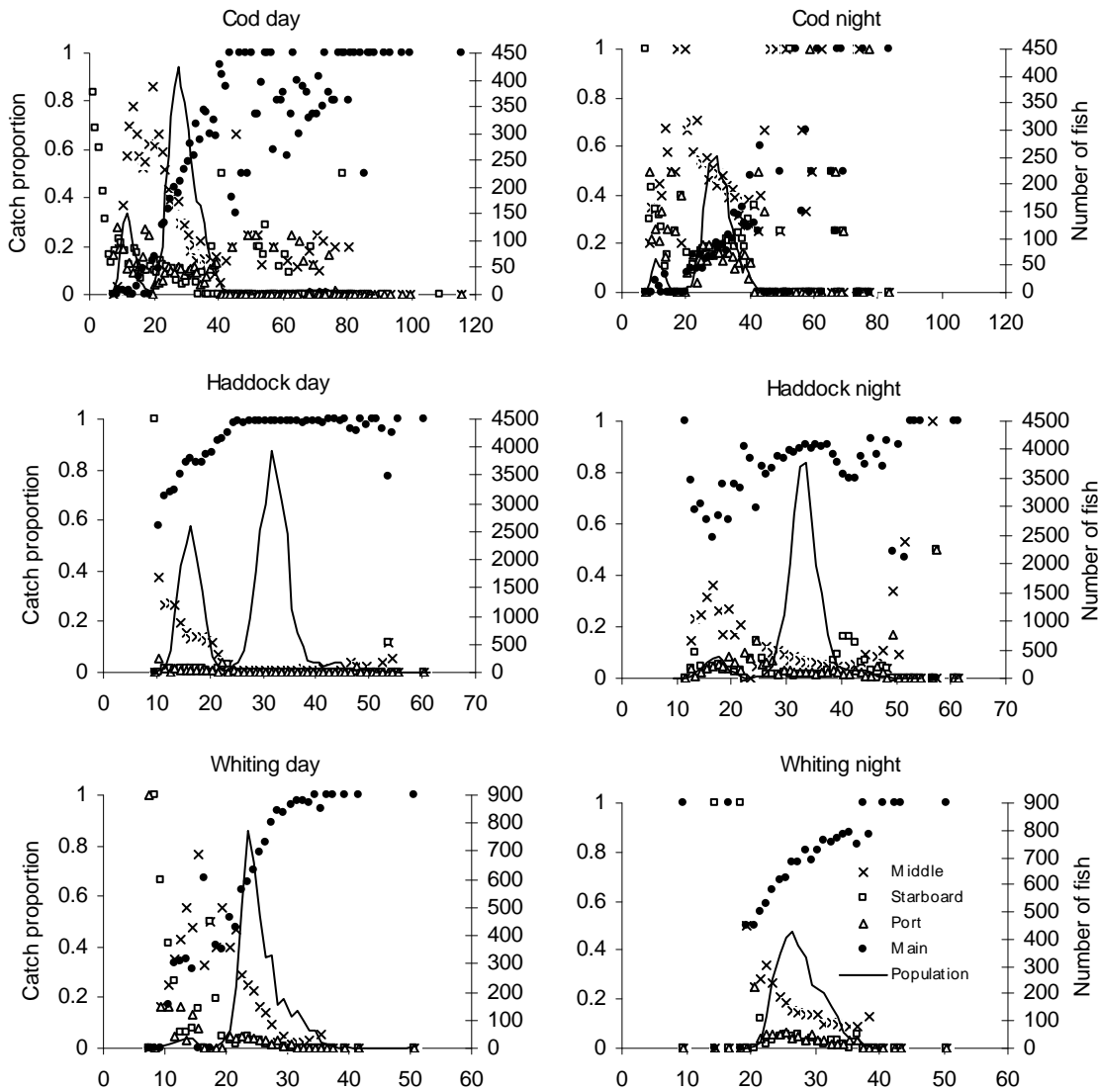


Fig. 2. Proportion of cod, haddock, and whiting caught in the four different codends by length and number of fish caught.

3.3 Horizontal species separation

The three lower compartments were about equal in size. A large proportion of the fish caught in these compartments was caught in the middle codend (Table 2). This suggests that most fish enter the trawl at the very centre of the ground gear. This is also where most of the escapement beneath the raised fishing line occurs. For haddock caught in the lower compartments during the day, the middle codend caught significantly more fish of all sizes ($P < 0.05$) compared to the

starboard and port codends (Fig. 2). At night, the difference in catch among the three lower compartments was significant only ($P < 0.05$) for small haddock below 20 cm long. For cod, the difference in catch among compartments was significant ($P < 0.05$) for fish below 30 cm long at night and below 20 cm long during the day. The catch proportions in the lower port and starboard codends were quite similar (Table 2); this indicates that the trawl was operating without systematic differences during the experiment.

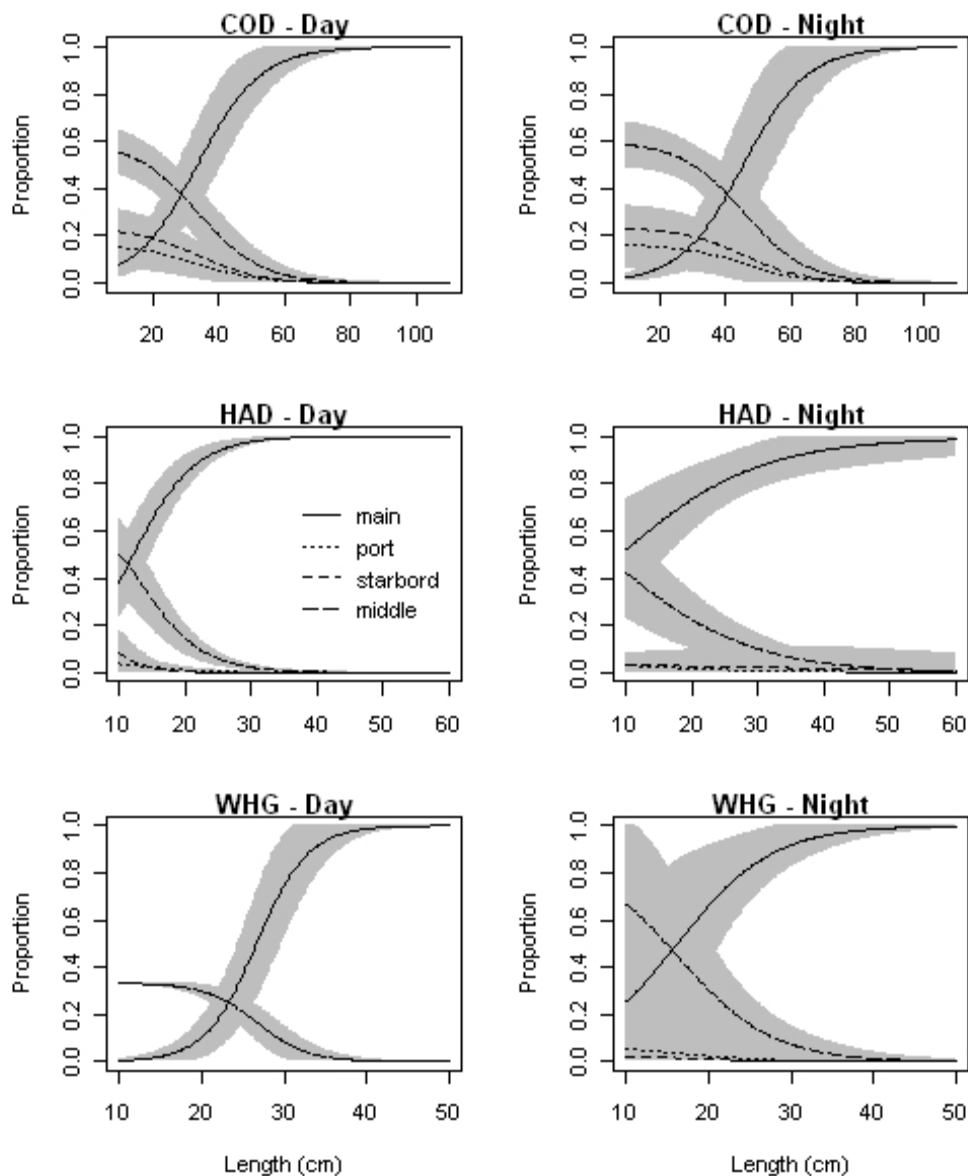


Fig. 3. Estimated catch proportion at length for cod, haddock, and whiting. Confidence limits (95%) are indicated with grey bands for the four codends; main codend = —, starboard codend = ---, port codend = ····, and middle codend = —·—.

4.0 Discussion

This experiment showed that the bycatch of cod, including large cod, in haddock-directed fisheries can be substantially reduced by raising the fishing line above the seabed; this change will make the exploitation of haddock and cod more independent of one another. The bycatch of cod can be substantially reduced from the fishery but not completely removed because especially larger cod still are caught. With our trawl, whiting and saithe will be caught efficiently along with haddock, whereas flatfish will escape beneath the trawl.

The length dependency and the day/night effect on the vertical separation on gadoids and flatfish can cause variation in the separation of species. Fish reaction to fishing gear is based primarily on vision (Glass and Wardle, 1995), thus changes in the physical parameters that affect fish vision can affect the behavioral response and introduce variation into the separation success. The total separation success also will be affected by the size structure in the exploited population and by the time of day during which fishing is conducted. The escapement beneath the raised fishing line will be high in a population that consists primarily of small cod and lower if the population consists of larger individuals. The diurnal effect observed in our study, where more cod went under the raised fishing line in the selective haddock trawl during the night than during the day, is in contrast to Ferro et al. (2007), in which significantly more cod entered the lower compartment during the day.

The separation success of the selective haddock trawls is encouraging compared to results for cod selection obtained with selective devices such as square mesh panels that currently are used (Krag et al., 2008). Recent experiments in which the separation of cod and haddock were stimulated using black tunnels (see Glass and Wardle, 1995) in the trawl extension caught 90% of the haddock in the upper compartment along with 60% of the cod (He et al., 2008).

Results of experiments using separator trawls exhibit a relatively consistent and high separation of haddock into the upper compartment even though these designs range from relatively low headline trawls (Main and Sangster, 1982; 1985) to higher headline designs (Engås et al., 1998; Ferro et al., 2007). The separation success for cod, however, is not so conclusive. Engås et al. (1998) reported a length dependency by which larger cod preferred the lower compartment, whereas Ferro et al., 2007 found no evidence of a systematic effect of cod length. One explanation for these differing results could be that the vertical distribution of species differs among areas (Engås et al., 1998). The escapement of fish beneath a ground gear in a survey trawl (Walsh et al., 1992) and in a commercial fish trawl (Ingolfsson and Jørgensen, 2006) exhibited contrasting length dependencies

to the separator trawl experiment reported by Engås et al., (1998) as primary small fish escaped the trawl beneath the ground gear. The length dependency by which small fish enter the trawl closer to the seabed compared to larger fish also has been found for American plaice (*Hippoglossoides platessoides*) and yellowtail flounder (*limanda ferruginea*) (Walsh, 1992). This may indicate that small individuals of demersal fish species in general enter a trawl closer to the seabed than do larger individuals. The size structure of the catch retained in the main codend may therefore be affected by the separation height. Ferro et al. (2007) suggested that light level and water clarity also influence the height at which fish enter the net mouth. In general, the experiments conducted with separator trawls have obtained a good separation of haddock and cod, but they have not provided a solution to selecting cod, including larger cod, out of the trawl.

Experiments have shown that fish that escape late in the catching process are more exposed to the consequence of injuries and exhaustion (Ryer, 2004). A major advantage of the selective haddock trawl is that unwanted bycatch will escape the gear with little or no physical contact with the gear. Moreover, benthic invertebrate marine species and rocks will pass beneath the raised fishing line and will not be mixed with the haddock catch, thereby potentially improving the quality of the catch. In a commercial version of the selective haddock trawl, the main codends fishing line would be raised above the traditional rock hopper ground gear and the three lower collecting bags would be removed. A lighter ground gear (e.g., with only a few large discs) could also be used to reduce the seabed disturbance and the towing resistance, as good bottom contact is not required to catch haddock, saithe, and whiting efficiently.

More fish were caught in the centre of the ground gear (middle compartment) than along the wings (starboard and port compartment), which is consistent with results reported by Walsh (1992) and Ingolfsson and Jørgensen (2006). This aggregation of fish in front of the center part of the ground gear is due to the herding process described in Wardle (1993). The centre section of the ground gear is therefore where species separation devices in the trawl mouth should be focused.

Holst and Revill (2008) reported a high reduction in the numbers of cod caught in their experiments using the Eliminator trawl in the North Sea mixed-species fishery. The Eliminator trawl has large meshes in the forward part of the trawl which gradually decreases towards the codend. These results indicate that the reduction of cod obtained with the selective haddock trawl could be further improved with large meshes in the lower belly section of the trawl.

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Paper 4



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The vertical separation of fish in the aft end of a demersal trawl.

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The vertical separation of fish in the aft end of a demersal trawl

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Krag, L. A., Holst, R., and Madsen, N. 2009. The vertical separation of fish in the aft end of a demersal trawl. – ICES Journal of Marine Science, 66: 772–777.

Two multi-compartment separator frames were used to study the vertical separation of some commercially important fish species in the aft end of a trawl, with the aim of separating cod (*Gadus morhua*) from other species. A non-linear multinomial model with random effects was used to analyse the data and to compare the performance of the two frames. The vertical distribution of cod in the aft end of the trawl was close to uniform, whereas haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangus*), plaice (*Pleuronectes platessa*), and lemon sole (*Microstomus kitt*) showed more uneven distributions. The use of guiding bars in the separator frame significantly ($p < 0.05$) increased the catch of cod, plaice, and lemon sole in the upper compartment. The vertical separation of cod was density-dependent; high densities of fish resulted in a more uniform distribution of cod. The species separations found differ from those reported from the studies of species separation in the region of the trawl mouth.

Keywords: cod, fish behaviour, multinomial mixed effects models, species selectivity, trawl.

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Introduction

The Danish demersal trawl operations in the Skagerrak and the North Sea are primarily mixed species fisheries. The economically most important species are plaice (*Pleuronectes platessa*), Norway lobster (*Nephrops norvegicus*), cod (*Gadus morhua*), monkfish (*Lophius piscatorius*), sole (*Solea solea*), lemon sole (*Microstomus kitt*), and turbot (*Psetta maxima*; Anon., 2006). The general conditions for exploiting these species have changed during recent years. Increasing effort regulations and the mandatory use of selective devices, such as square-mesh panels, increased codend mesh size, and grids, have been implemented to help rebuild the declining North Sea and Skagerrak cod stocks. Effort regulations and closed areas impact the fishery of all species, not just cod, so an alternative to non-specific measures is to develop further more species-selective fishing gear. Glass (2000) stated that fish escape-ment can be influenced by species-specific behaviour patterns and mechanical sorting mechanisms based on size. Despite the distinct morphological differences among cod, flatfish, and *Nephrops*, it is not possible to exclude cod of all sizes by pure mechanical sorting without the loss of target species.

Behavioural studies in the trawl mouth have shown that haddock and, to a lesser extent, whiting and saithe (*Pollachius virens*) rise above the groundgear as they tire. Cod, flatfish, and *Nephrops* enter the trawl close to the groundgear (Main and Sangster, 1981; Thomsen, 1993; Bublitz, 1996). These findings have led to extensive studies of species separation in the mouth of the trawl (Main and Sangster, 1982, 1985; Cotter *et al.*, 1997; Engås *et al.*, 1998; Ferro *et al.*, 2007). Behavioural aspects farther aft in the trawl have been studied less, but cod apparently rise towards the upper panel farther aft in trawls, whereas flatfish glide backwards closer to the lower panel (Thomsen, 1993). Scottish experiments have shown that rising ropes in a trawl

mouth can divert cod towards the upper panel of trawls (R. S. T. Ferro, formerly FRS, pers. comm.).

The objective of this study was to investigate how efficiently cod can be separated from other fish species in the aft end of a trawl. It is important to be able to distinguish between different species and sizes when using camera observation techniques, and it is difficult, especially for flatfish (Thomsen, 1993; Bublitz, 1996). Here, we assess the vertical separation of the different species using a separator frame with three vertically stacked compartments. A second separator frame with guiding bars was tested to determine whether additional stimuli could improve the separation of cod from other fish. We used a non-linear multinomial model with random effects to analyse the catch data collected with the two separator frames. Further, the vertical separation of species by each of the two types of frame was quantified and compared.

Material and methods

Experimental set-up

Two combined fish and *Nephrops* trawls of a design typically used by the Danish fleet in the North Sea mixed fishery were manufactured by Cosmos Trawl in Hirtshals, Denmark. Both were modified with identical four-panel aft ends by inserting two wedges into the original two-panel design (Figure 1). The four-panel construction provided a stable cavity in the aft section. Both trawls were mounted with a square, rigid, separator frame that separated fish into three vertically stacked compartments. The square cavity in the extension section, in which the separator frames were installed, was ~0.9 m wide and 1.0 m high. The separator frames were installed two meshes behind the joint between the last tapered belly section and the extension, at an angle of ~50°, which equals 12 m in front of the codline. The frames were installed at an angle and not vertically to allow haul-back of the

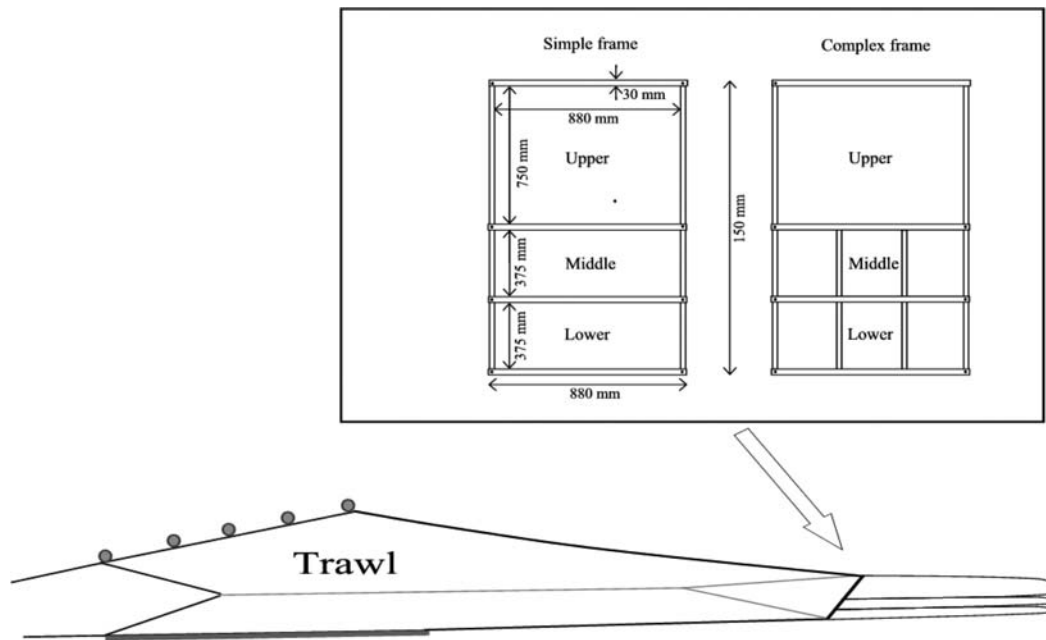


Figure 1. A drawing of the separation section in the trawl and the simple and complex separator frames, each with three vertical compartments.

gear through the vessel’s relatively narrow stern ramps and the frames to be rolled up onto the net drums. The two frame types are denoted simple (S) and complex (C), and the three compartments in each frame are denoted lower, middle, and upper. Small-mesh codends (42 mm full mesh) were attached to each compartment. The complex frame differs from the simple frame in its presence of two vertical guiding bars across the lower and middle compartments. The distance of 28 cm between the two vertical bars in the complex frame was too large to cause mechanical selection of most fish species. The upper compartment covered 50% of the frame opening, and the middle and lower compartments covered 25% each in both frames. The compartments were of unequal size to obtain more detailed information about the separation of cod and flatfish in the lower part of the gear. The frames were constructed of horizontal polyamide bars and vertical fibreglass bars.

Sea trials were conducted on board a 511-kW commercial vessel using the twin-trawl technique (Wileman *et al.*, 1996) on commercial fishing grounds in the Skagerrak (ICES rectangle 44F9). In all, 11 hauls were taken between sunrise and sunset in depths varying from 30 to 90 m. Haul duration was 90 min at 3.1 knots. Experimental conditions were recorded for each haul. The catch in the six compartments (three from each trawl) was kept separate during all stages of the handling process. All commercially important species (plaice, lemon sole, cod, haddock, saithe, and whiting) were measured to the nearest centimetre, and the midpoints of the length classes were used in subsequent data analysis.

Statistical modelling

The aim of the analysis was to model the separation of fish into the three stacked compartments and to compare the catches of the two frames. Each haul was considered a cluster, and random variation between the hauls was assumed (Fryer, 1991).

Single-haul model

The numbers of fish collected from the compartments are denoted $n_{f,g}$, where $f = \{S, C\}$ for the simple and complex frames and $g = \{L, M, U\}$ for lower, middle, and upper compartments. The numbers of fish collected from each of the two frames are denoted n_{S+} and n_{C+} , and the grand total is $n_+ = n_{C+} + n_{S+}$.

The conditional distribution for the number of fish entering each compartment given the total number for each frame is multinomial, i.e. $(n_{f,U}, n_{f,M}, n_{f,L} | n_{f+}) \sim MN(n_{f+}; \pi_{f,U}, \pi_{f,M}, \pi_{f,L})$ $f = \{S, C\}$; $\pi_{f,U} + \pi_{f,M} + \pi_{f,L} = 1$. This model implicitly assumes independence among fish movements. Schooling behaviour or local abundance effects may violate this assumption and cause overdispersion in the data. Using the upper compartment as baseline category, the probabilities can be written as

$$\begin{aligned} \pi_{f,U} &= \frac{1}{1 + \exp(\eta_{f,M}) + \exp(\eta_{f,L})} \\ \pi_{f,M} &= \frac{\exp(\eta_{f,M})}{1 + \exp(\eta_{f,M}) + \exp(\eta_{f,L})} \\ \pi_{f,L} &= \frac{\exp(\eta_{f,L})}{1 + \exp(\eta_{f,M}) + \exp(\eta_{f,L})} \end{aligned} \quad f = \{S, C\}.$$

This model is linear in the sense that

$$\text{logit}(\pi_{f,g}) = \log\left(\frac{\pi_{f,g}}{\pi_{f,U}}\right) = \eta_{f,g} \text{ and } f = \{S, C\}; \quad g = \{M, L\}.$$

A split parameter, p , that gives the conditional probability that a fish enters, say, rig C given that it entered one of the rigs is required for simultaneous modelling of all six compartment probabilities. The conditional distribution for the six compartments

given the grand total is a multinomial:

$$(n_{C,U}, n_{C,M}, n_{C,L}, n_{S,U}, n_{S,M}, n_{S,L} | n_+) \sim \text{MN}(n_+; \varphi_{C,U}, \varphi_{C,M}, \varphi_{C,L}, \varphi_{S,U}, \varphi_{S,M}, \varphi_{S,L}),$$

where

$$\varphi_{C,g} = \frac{\pi_{C,g}}{p} \text{ and } \varphi_{S,g} = \frac{\pi_{S,g}}{1-p} g = \{U, M, L\}.$$

This model is not linear in the sense described above. Apart from the usual concerns for non-linear models (Hougaard, 1982), the non-linearity may also be of relevance for the choice of tool for fitting the model.

Multiple-haul model

We extended the model to all hauls, using index h for a given haul and H for the total number of hauls. A random haul effect was introduced by adding a random variable to each of the four linear predictors:

$$\eta_{f,g,h} = \eta_{f,g} + b_{f,g,h} \quad f = \{S, C\}; g = \{M, L\}, h = \{1, \dots, H\},$$

where $\eta_{f,g}$ now denotes the mean predictor for compartment g in frame f . The vector of random effects for haul h was assumed to be multivariate normally distributed:

$$\mathbf{b}_h = (b_{C,M,h}, b_{C,L,h}, b_{S,M,h}, b_{S,L,h})^T \sim \text{MVN}(\mathbf{0}, \mathbf{\Omega}), h = \{1, \dots, H\}.$$

Testing for differences between frames

The single haul model described above is general in that it allows for the two frames to have different (conditional) cell probabilities. A more parsimonious model was assessed by testing whether corresponding compartments had identical (conditional) cell probabilities:

$$H_0 : \pi_{S,U} = \pi_{C,U} \text{ and } \pi_{S,M} = \pi_{C,M} \text{ (and hence } \pi_{S,L} = \pi_{C,L})$$

$$H_1 : \text{at least one of the pairs differed.}$$

This test was suitable for choosing the frame best suited for species separation across all species. The hypothesis was tested using a likelihood ratio test. The constrained model 2, corresponding to the null hypothesis, was fitted, and twice the difference in the log-likelihood is referred to as the $\chi^2_{d.f.=2}$ distribution with 2 degrees of freedom (d.f.) reflecting the difference in the number of parameters.

We used the software package ADMB-RE (Fournier, 2006) for parameter estimation. We encountered numerical problems when trying to estimate a full variance-covariance $\mathbf{\Omega}$ matrix. The matrix was therefore assumed to be of diagonal form, setting all covariances to zero.

Results

Sea trials

The separator frames proved to be simple to use on commercial vessels. Operational conditions experienced during the 11 hauls were similar, with windspeed ranging from 2 to 13 m s⁻¹ and door spread from 145 to 189 m. The length distributions and catch size in the upper, middle, and lower compartments for the

simple and complex frames were similar for most species, when taking into account the fact that the upper compartment was twice as large as the other two (Figure 2). The catch of cod, haddock, saithe, and whiting consisted primarily of smaller fish below their respective minimum landing sizes (MLS). The total numbers of fish caught by the two trawls differed for whiting and saithe, for which larger numbers were caught in the trawl with the simple frame. The number of individuals per species varied from a few hundred (saithe) to several thousand (cod).

Statistical modelling

In model 1, separate probabilities for each compartment and frame were estimated, whereas model 2 assumes equal probabilities for corresponding compartments of the two frames. Model 2 was compared with model 1 using a likelihood ratio test. The drop in deviance (i.e. the χ^2_2 value) was significant ($p < 0.05$) for all species: 163.2 for cod, 84.8 for haddock, 108.6 for whiting, 48.9 for plaice, and 228.3 for lemon sole. Therefore, the vertical separation of all species was significantly affected by the guiding bars in the complex separator frame.

Vertical separation

Table 1 gives the estimated conditional mean catch probabilities for each compartment in the two separator frames for all species (model 1). The catch of cod in the upper compartment was estimated to be 54% for the simple frame and 67% for the complex frame. Haddock and whiting were caught mainly in the upper compartment in both separator frames, whereas plaice and lemon sole were caught primarily in the lower compartments of the simple frame. Higher catch proportions of plaice, lemon sole, and whiting were estimated in the upper compartment in the complex frame relative to the simple frame; in particular, the proportions of plaice and lemon sole in the simple frame were almost double those in the upper compartment in the complex frame. The catch proportion in the upper compartment in the complex frame was higher than that in the simple frame for all species except haddock, for which it was 87% in the simple frame and 78% in the complex frame. Saithe were caught in a few tows only, so were excluded.

A variant of model 1, which used total counts of fish by frame as a covariate, converged only for cod. The vertical separation of cod was density-dependent (Figure 3). The catch proportion of cod in the upper compartment was highest at low densities of fish, but decreased towards a uniform distribution at higher levels of mean density of fish caught during the tow (Figure 3).

Discussion

Our study investigated the potential for separating different fish species at the aft end of a demersal trawl, in contrast to most other studies in which species are separated in the trawl mouth (Main and Sangster, 1982, 1985; Engås *et al.*, 1998; Ferro *et al.*, 2007). Most individuals of each species were caught either in the upper or in the lower compartment during studies describing separation at the trawl mouth. The separation of species between compartments was not as consistent at the aft end of a trawl as in the trawl mouth area. The vertical separation of cod shifted from a preference for the lower compartment in the trawl mouth to a more uniform distribution at the trawl aft end, illustrated by the catch proportions in the compartments being almost proportional to the size of the compartments. This shift in vertical behaviour agrees with the camera observations

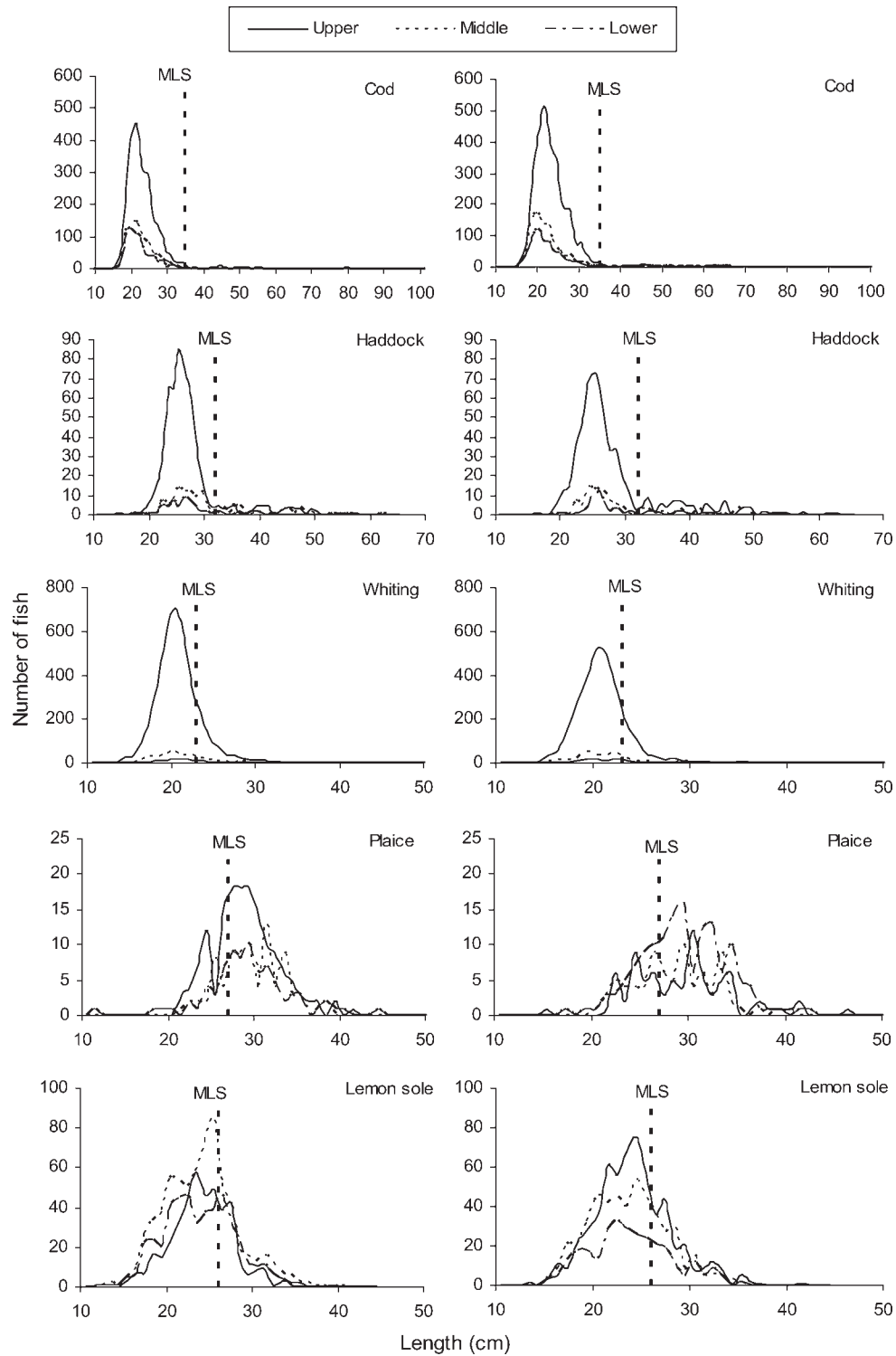


Figure 2. Length frequency of vertical catch distributions of cod, haddock, whiting, plaice, and lemon sole for all hauls combined. Catch values for the simple frame are in the left column and for the complex frame in the right column. MLS is the minimum landing size.

described by Thomsen (1993). The vertical separation of plaice and lemon sole also differed from that reported from trawl mouth studies. Those species rose towards the upper panel at the aft end, as observed for cod, but in lesser proportions. These findings for aft separation of flatfish are in accord with results from the western Atlantic (He *et al.*, 2008). The apparent strong

affinity for the lower panel at the trawl mouth therefore appears to be less obvious in the narrow extension leading to the codend. Thomsen (1993) reported that flatfish were frequent close to the upper panel at the aft end of a tapered section; that section had a diameter of ~ 1 m, a similar dimension to the separation section used in the present study. A better separation of cod

Table 1. Estimated conditional catch proportions for the three compartments in the simple separator frame and in the complex separator frame, by species.

Species	Compartment	Simple frame		Complex frame	
		Estimate	s.e.	Estimate	s.e.
Cod	Upper	0.540	0.051	0.671	0.044
	Middle	0.282	0.033	0.194	0.027
	Lower	0.178	0.021	0.136	0.019
Haddock	Upper	0.872	0.088	0.777	0.075
	Middle	0.088	0.061	0.151	0.055
	Lower	0.040	0.028	0.072	0.026
Whiting	Upper	0.906	0.029	0.951	0.011
	Middle	0.082	0.027	0.038	0.009
	Lower	0.011	0.003	0.011	0.003
Plaice	Upper	0.268	0.033	0.538	0.069
	Middle	0.265	0.026	0.209	0.041
	Lower	0.468	0.031	0.253	0.043
Lemon sole	Upper	0.326	0.042	0.502	0.038
	Middle	0.385	0.027	0.305	0.027
	Lower	0.289	0.021	0.194	0.018

Model 1 was used to estimate the catch proportions. s.e., standard error.

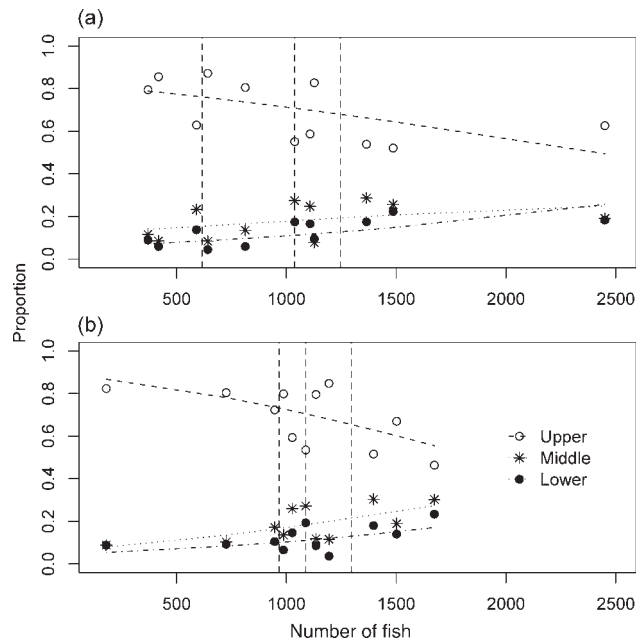


Figure 3. Estimated separation success for cod in numbers from the upper, middle, and lower compartments as a function of fish density: (a) simple frame, and (b) complex frame. The dashed vertical lines indicate from the left the lower quartile, the median, and the third quartile.

and flatfish may therefore be obtained farther forward in the gear. Haddock and whiting in the current study, however, exhibited vertical separation at the narrow aft end, similar to that reported in trawl mouth studies. Some 90% of haddock and whiting entered the upper compartment along with about half the cod. Results from experiments with square-mesh panels at the aft end of demersal trawls show that such devices are more effective in separating juvenile haddock and whiting than they are in separating

out juvenile cod (Madsen *et al.*, 1999; Krag *et al.*, 2008). The species-specific differences in vertical preferences within the trawl extension may provide an explanation as to why some species escape through square-mesh panels more efficiently than others. The vertical separation of fish shown here was based primarily on fish smaller than their respective MLS, except for plaice. The vertical behaviour may be different in a population containing mainly large fish.

The catch proportion of cod in the upper compartment (54%) of the simple frame corresponded well with the size of the openings of the upper compartment (50%). In contrast, the complex frame elevated more cod into the upper compartment (67%) than did the simple frame. Similar results for stimulated separation of cod are presented by He *et al.* (2008), ~60% being caught in the upper codend during separation in the extension of the trawl. He *et al.* (2008) used a visual illusion created by a black tunnel (see also Glass and Wardle, 1995) to enhance vertical separation. The catch of plaice and lemon sole in the upper compartment also increased considerably. In contrast to all other species and expectation, haddock separation into the upper compartment was less in the complex frame than in the simple frame. We have no explanation for this observation. The guiding bars in the complex frame clearly influenced vertical separation, but the complex frame did not improve the separation of cod from other roundfish or from flatfish. The results from the complex frame with guiding bars indicate that a relatively large proportion of fish can be elevated in the trawl cavity by a simple stimulus. Traditional sorting grids are made with a fixed bar spacing to provide mechanical selection when the behaviour of fish is of less importance for the selection process. Such sorting systems are efficient in releasing fish below or above a certain size, but they can also incur relatively high losses of target species (Fonseca *et al.*, 2005).

The vertical separation of cod was density-dependent. Most cod were caught in the upper compartment at low fish density, but the catch was more proportional to the area of the frame opening at higher densities. A possible explanation for this finding is that many fish species have a predisposition to stay a certain distance away from other fish and netting or other fishing gear components and that this will tend to space them out evenly. The variations in the vertical separation of fish may therefore be larger from haul to haul and within hauls in narrow gear sections than in larger gear sections, such as the trawl mouth.

All catch data in this study were obtained during daylight. Ferro *et al.* (2007) found that a significantly greater proportion of cod, plaice, and lemon sole entered the lower compartment by day than by night and that the rising behaviour of gadoids in the catching process appeared to be more pronounced during daylight. Fishing gear designs making use of behavioural differences must obviously rely on these differences to be relatively consistent over time and across regions. Anything that alters the standard gear design might affect how fish behave inside the gear. This seems to be the case with the separator frame, but direct observations of how fish behave as they encounter the separator frame in the trawl are necessary to quantify fully the possible effects of the sampling device.

In summary, the rather distinct vertical fish separation reported from species separation studies conducted in the trawl mouth area was not found at the narrow aft end of the trawl. Behaviour-based efficient vertical separation of cod from other roundfish, such as haddock, saithe, or whiting, is therefore difficult at that point in

the trawl. The separation success between cod and flatfish was higher than for cod and other roundfish, but was still relatively poor. Cod and flatfish were, however, separated better at the aft end than in the area of the trawl mouth. The guiding bars in the complex frame showed that fish behaviour within a trawl can be affected by simple means. The approach could be used to separate fish from *Nephrops* in the *Nephrops* fisheries, where discard rates are high (Krag *et al.*, 2008). Moreover, simple guiding systems could be used to increase the probability of contact with selective devices such as square-mesh panels.

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