Chapter 4

# Trawl Selectivity in the Barents Sea Demersal Fishery

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Additional information is available at the end of the chapter

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**Abstract**

This chapter provides a general overview of the Barents Sea demersal trawl fishery. First, it reviews historical catch levels and current biomass status of four commercially important demersal species (cod, haddock, Greenland halibut, and redfish) and includes an overview of their management plan that has been carried out by the Joint Norwegian–Russian commission. Then, it presents the evolution of the technical regulations for improving size selectivity in this fishery and describes current challenges in gear selectivity. Later, this chapter describes the concept of size selectivity, introduces the selective parameters that define a selection curve, and progressively introduces different parametric models that describe the selection process. The most common experimental methods and gear used to collect selectivity data are described, and their advantages and disadvantages are discussed. Finally, this chapter describes an alternative, or a complementary method, to the conventional estimation of trawl selectivity—the FISHSELECT method. This method is based on morphology measurements and fish penetration models to estimate the selective properties of different mesh shapes and sizes at different mesh openings, which are later used to provide simulation-based prediction of size selectivity. FISHSELECT has already been applied to four important species of the Barents Sea Demersal Fishery, and the results have in all cases showed to be coherent with the results obtained from sea trial results.

**Keywords:** selectivity, trawl, bottom trawl, Barents Sea, demersal fishery, FISHSELECT

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## 1. Introduction

The main target species for the Norwegian bottom trawling fleet north of 62° N are the Northeast Arctic cod (*Gadus morhua*), haddock (*Melanugrammus aeglefinus*), and saithe (*Pollachius virens*); all of these species belong to the gadoid family. During the past 20 years, the catches of cod have averaged 625 649 tonnes per year, with the largest landing being in 2014 (986 449 tonnes) [1]. During the same period, the catches of haddock and saithe averaged, respectively, 165 222 and 162 578 tonnes per year, with the largest landing for haddock registered in 2012 (315 627 tonnes) and for saithe in 2006 (212 822 tonnes) [2, 3]. Of these catches, approximately 83% of cod, 90% of haddock, and 97% of saithe were harvested by Norwegian and Russian vessels; the rest was caught by vessels from Iceland, Greenland, and the EU [1–3]. In 2014, nearly 70% of the total catch of cod, 76% of haddock, and 49% of saithe were fished by bottom trawlers. The rest of the quota for these species was fished by gillnetters, longliners, jiggers, and demersal seiners [1–3]. Other commercially important species, mostly caught as bycatch in this fishery, are redfish (*Sebastes marinus*) and Greenland halibut (*Reinhardtius hippoglossoides*).

A key strategy of the Norwegian–Russian fishing legislation is to minimize the capture of undersized fish. When more than 15% of the catch (by numbers) is undersized, the fishery is closed. Moreover, the discard of dead or dying fish from regulated species is forbidden in this (Norway–Russian) fishery. The aim with size selection is to reduce the capture of undersized fish while also reducing the loss of fish above the minimum legal size (MLS). To achieve this goal, the use of sorting grids with a minimum bar spacing of 55 mm is currently mandatory in all trawls fishing for gadoids in this fishery.

Assessments of the Joint Norwegian–Russian Fisheries Commission show that the Northeast Arctic cod stock is in a fairly good state. The spawning biomass in 2013 was estimated at 2 million tonnes, while the total stock biomass was estimated to be around 3.5 million tonnes [1]. The International Council for the Exploration of the Sea (ICES), which is a global organization that develops science and advice to support the sustainable use of the oceans, advises the Joint Russian–Norwegian Fisheries Commission to set a total allowable catch (TAC) of 805 000 tonnes in 2016 [1].

The Northeast Arctic haddock and saithe stocks are considered to be in good condition. ICES advises that when the Joint Russian–Norwegian Fisheries Commission management plan is applied, landings in 2016 should not exceed 223 000 tonnes for haddock and 140 000 tonnes for saithe [2, 3].

## 2. Technical regulations for improving size selectivity

In 1979, the Northeast Atlantic Fisheries Commission (NEAFC) agreed to increase the mesh size of codends made of cotton, polyamide, and polyester from 120 to 125 mm. As of 1 January 1980, the minimum legal size of cod and haddock that could be kept was set at 39 and 35 cm, respectively; in addition, the catches of undersized fish could not exceed 15% (by weight) of the catch [4]. In 1982, the NEAFC increased the commercial sizes of cod and haddock to 42 and 39 cm, respectively, and established that the bycatch of undersized fish should not exceed 15% (by numbers) of the catch. Norway also unilaterally increased the minimum mesh size of trawl codends to 135 mm regardless of the trawl material [4]. In 1983, a discard ban was introduced into the fishery [5]; it stated that vessels were obliged to land also the catches of all undersized fish. A surveillance program established during 1983–1984 showed that substantial areas need to be closed to the commercial fishery due to the high proportions of undersized cod and haddock in the catch. Typical catches in these areas could contain 30–50% of juvenile fish (by numbers). Therefore, the temporary closure of certain fishing areas led to a less efficient fishery because the fleet had to search for other areas to fish on [6].

Between 1985 and 1991, researchers in Norway conducted selectivity experiments that aimed at improving size selectivity of bottom trawl codends. These experiments considered different mesh configurations, round straps, different top and bottom panels, codend twine materials, and sorting grid systems [7, 8]. The methods found to be most practical were the shortened lastridge ropes (12–15% reduction) and the escape grids (Sort-X system). The shortened lastridge ropes gave similar size selection estimates as square mesh codends. However, square mesh codends were associated with meshing of fish, and especially redfish, and maneuvera-bility challenges on deck [9].

Even though the Sort-X sorting grid represented a revolutionary method for improving selectivity in trawl codends, in 1990 the Norwegian Directorate of Fisheries, in 1990, increased the minimum size of cod to 47 cm and of haddock to 44 cm. According to this institution, an alternative mean of resource management had to be enforced in the fishery because the development of technical codend modifications had still not given the expected results [10].

Between 1990 and 1996, experiments with sorting grids that aimed at reducing the catch of young fish were conducted in Norway and Russia [11, 12]. In 1995, the Joint Russian–Norwe-gian selectivity experiments on cod in the Barents Sea proved that the selectivity of the Russian single-steel grid system "Sort-V" and that of the double steel grid system "Sort-X" were similar [12]. Based on the results of these experiments, as of 1 January 1997 both types of grids with 55-mm interbar space began to be used in cod and haddock fisheries in some limited areas of the Barents and Norwegian Seas (**Figure 1**). Later, the Institute of Marine Research of Norway satisfactorily adapted the Sort-V system to Norwegian trawlers [13, 14]. The new system, which is known as the Single grid and only includes some slight changes from the Sort-V system, was legalized by the Norwegian Directorate of Fisheries in 2000.

Since their introduction, the Sort-X, Sort-V, and Single grid have been associated with crew safety problems, especially when handling the grid sections in bad weather. During the late 1990s, experiments with grids made of other materials, such as plastics, fibreglass, nylon, and rubber, were promoted. The intention behind these experiments was to offer the industry grids that could be more easily handled, were more user-friendly, and were cheaper to purchase [15]. The systems studied were the plastic Sort-X, the Eurogrid, and the Flexigrid. The plastic Sort-X was made of high-density polyethylene (HDPE) materials and weighed considerably less than the steel version. The Eurogrid was made of massive nylon and was developed primarily for the trawl fishery in the North Sea [16]. Although these grids were designed to be more user-friendly alternatives to other grids on the market because of their low weight, flexibility, and the possibility of storing them in net drums, none of them was successfully introduced into the fishery. During three years of experimental work, the Flexigrid (made of Polyamide (PA) bars and rubber frames) (**Figure 1**) proved to have a selection capacity similar to that of the Sort-X [17–20]. This new grid system was lighter, smaller, more flexible, and therefore easier to handle on deck. Thus, the Flexigrid system was legalized in the beginning of 2002.

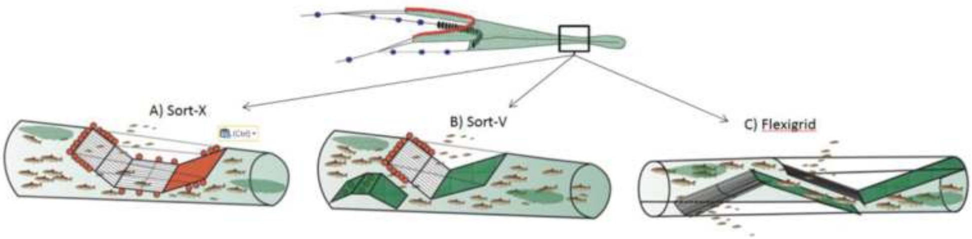


**Figure 1.** Mandatory sorting grids in the Barents Sea Demersal Fishery: (A) Sort-X, (B) Sort-V, and (C) Flexigrid.

Between 2004 and 2008, further experiments with escape panels were performed in the Barents Sea [21]. Despite the results showing similar selective performance to mandatory sorting grids [22, 23], escape panels were not considered as an alternative selection device for the Barents Sea Demersal Fishery.

Today, all four sorting grids described above are legal with a minimum grid bar spacing of 55 mm: the Sort-X, Sort-V, Single grid, and Flexigrid. The Sort-V and the Single grid system are still used by some vessels, but the system employed by the majority of vessels today is the Flexigrid. The two main reasons for fishermen to prefer the flexigrid system are that (a) it is a safer grid to use on deck, especially in bad weather, and (b) the retention of fish above the minimum size for cod and haddock is higher for the flexigrid than for the Sort-V/Single grid [24]. This second argument became especially important when in 2011 the minimum legal size was reduced from 47 to 44 cm for cod and from 44 to 40 cm for haddock. This reduction in minimum size resulted from the Russian–Norwegian joint meetings and the aim of standardizing the regulations for the Barents Sea. This reduction in minimum sizes was also accompanied by a reduction in the minimum codend mesh size. Thus, in addition to the grid, trawlers can today use codends with a minimum diamond mesh size of 130 mm.

The rapid increase in the biomass of Atlantic cod in the period 2008–2014 has brought some unusual challenges for the Barents Sea trawlers, which have often met really high concentrations of cod in the fishing grounds. From the beginning, these high concentrations at sea were quickly reflected in reduced sorting capacity of sorting grids. The high catch rates encountered by the grid sections have led not only to reduced selection performance of the grids but also to more serious problems like breakage of grids and grid sections. Underwater recordings have shown that fish accumulates both in front and behind the grid [25] and does not fall back in the codend. Because the catch sensors are placed in the codend, the skipper does not receive any information on the ongoing catch accumulation in the gear. The consequence of this process is unwanted big catches that exceed the vessel's processing capacity and lead to reduced quality of the catch [25].

The main reason for the accumulation of fish in front and behind the grid is related to the reduction in water flow created by the presence of the grid section and especially the sorting grid(s) [26]. In the past years, there have been efforts to increase the water flow in the grid sections to try to mitigate the fish accumulation problem. If the water flow is too high, grids lose their selective properties and fish can flow through the section without having a chance to contact the grid. Sorting grid sections have traditionally been constructed as two-panel constructions, but in an attempt to improve the flow conditions in the section new four-panel constructions have been tested in the past years. Gjøsund et al. [26] showed that a four-panel Single grid section allows higher water flow through the section than an equivalent two-panel grid section. Because the tests carried out at sea also indicate that at high catch rates four-panel sorting grid sections with larger cross-section areas perform better than two-panel grid sections (Sort-X, Sort-V, and Flexigrid) (own data, unpublished), the use of these types of sections was legalized in 2014 and 2015.

## 3. Description of size selectivity

Selective fishing refers to the ability of a fishing method to target and capture fish by size and/ or species. Size selective fishing in the Barents Sea demersal trawl fishery aims at avoiding catching fish below the minimum landing sizes that enters the fishing gear while simultaneously having high probability of retaining fish above the minimum size. In the Barents Sea demersal trawl fishery, the selective devices in the fishing gear consist of a sorting grid followed by a size selective codend. The grid enables releasing fish up to a certain size through the grid, provided that they are able to find their way out between the bars. Fish that do not manage to escape through the grid fall back into the codend where they have an additional chance to escape through the meshes, provided that they are not too big to be able to pass through them. It is obvious that based on this system only fish below a certain size will have a chance to escape through the grid or codend meshes. The smaller the fish the easier they will fit through between the grid bars and through the codend meshes. Therefore, it is to be expected that the retention probability for a fish entering the gear will increase with the size of the fish. For the description of the size selection in a fishing gear, it is convenient to use a parametric mathematical model that is able to describe the retention probability $r$ of the fish as a function of its length $l$. Traditionally, as for many other fisheries and trawl constructions the combined size selection of the grid and codend for the species in the Barents Sea demersal trawl fishery has been described by the *logit* size selection model:

$$r(l, L50, SR) = \frac{\exp\left(\frac{\ln(9)}{SR} \times (l - L50)\right)}{1.0 + \exp\left(\frac{\ln(9)}{SR} \times (l - L50)\right)} \quad (1)$$

In a *logit* size selection model, the retention probability will increase monotonously with the length of the fish. The size selection for this model is fully defined based on the value of the two parameters *L50* and *SR*. *L50* can be interpreted as the length at which a fish will have 50% probability of being retained by the fishing gear conditioned that it enters the gear. *SR* can be interpreted as the difference length between fish with, respectively, 75% and 25% of being retained in the fishing gear conditioned they enter it. **Figure 2** illustrates the *logit* size selection model and the meaning of the selection parameters L50 and SR.

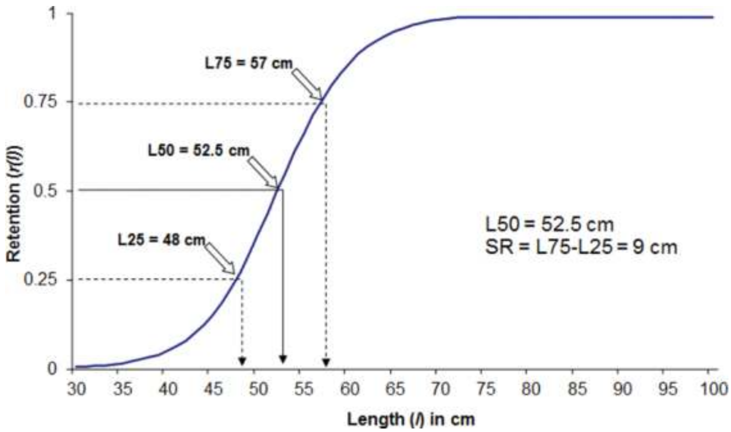


**Figure 2.** A selection curve that describes the *logit* size selection model.

Based on the values of *L50* and *SR* for a *logit* size selection model, the length *Li* of a fish with *i* % of being retained can be calculated by:

$$Li = L50 + \frac{SR}{\ln(9)} \times \ln\left(\frac{0.01 \times i}{1.0 - 0.01 \times i}\right) \quad (2)$$

Several studies have aimed at quantifying size selection for cod and haddock in the selective systems deployed in the Barents Sea demersal trawl fishery in terms of the values for L50 and SR using the *logit* size selection model [11, 13, 14, 16, 21, 22].

However, the *logit* size selection model presents some limitations which are important when considering the size selection systems used in the Barents Sea demersal trawl fishery. First, it

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does not explicitly reflect the dual nature of the size selection of a system consisting of a size selective grid preceded by a size selective codend. This can lead to a poor description of the size-dependent retention probability in the fishing gear in cases where the size selective properties of the grid and the codend differ considerably. Second, the *logit* model does not enable quantifying the individual contributions of the grid and the codend to the combined size selection in the gear. This is an important limitation when trying to improve size selection based on implementing gear modifications. Third, the *logit* model is not able to account for that not necessary all fish are able to make contact with the grid during their drift towards the codend. Besides potentially leading to a poor overall description of the size selection in the gear, this limitation also disables the quantification effect on the sorting efficiency of the grid by, for example, changing grid area size or making modifications to the lifting panel ahead of a Sort-V/Single grid section.

Based on the above-mentioned limitations, recent studies on the size selection in the Barents Sea demersal trawl fishery [30] have applied a more complex dual size selection model $r_{dual}$ that accounts for all of these limitations:

$$r_{dual}\left(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend}\right) = \left(1.0 - C_{grid} + C_{grid} \times logit\left(l, L50_{grid}, SR_{grid}\right)\right) \times logit\left(l, L50_{codend}, SR_{codend}\right) \tag{3}$$

The dual size selection model contains five parameters, $C_{grid}$, $L50_{grid}$, $SR_{grid}$, $L50_{codend}$, and $SR_{codend}$. The first three describe the size selection in the grid while the last two describe the size selection in the codend. The parameter $C_{grid}$ quantifies the proportion of fish entering the grid section that makes contact with the grid and is size selected by it. For the fish that makes contact with the grid, their size selection is described by a *logit* model with the parameters $L50_{grid}$ and $SR_{grid}$. For the codend, the size selection is described by an additional *logit* model with the parameters $L50_{codend}$ and $SR_{codend}$.

The grid contribution to the combined size selection is described by Eq. (3) (the term in the first brackets) and is named as the *clogit* size selection model [31]:

$$r_{clogit}\left(l, C_{grid}, L50_{grid}, SR_{grid}\right) \equiv 1.0 - C_{grid} \times \left(1.0 - r_{logit}\left(l, L50_{grid}, SR_{grid}\right)\right) \tag{4}$$

Model (4) quantifies the length-dependent retention probability for that (conditioned it entered that part of the trawl) a fish is still inside the trawl after it has passed through the section of the trawl where the grid is installed. Based on Eq. (4), Eq. (3) can be simplified to:

$$r_{dual}\left(l, C_{grid}, L50_{grid}, SR_{grid}, L50_{codend}, SR_{codend}\right) = r_{clogit}\left(l, C_{grid}, L50_{grid}, SR_{grid}\right) \times r_{logit}\left(l, L50_{codend}, SR_{codend}\right) \tag{5}$$

## 4. Experimental methods for collecting selectivity data

The selectivity of fishing gear should be measured under conditions that mimic commercial fishing. Ideally, the sea trials should be undertaken on commercial fishing grounds, at commercial fishing depths, at commercial catch rates and sizes, and during the commercial fishing season. It is well known that variations in the environmental conditions or fish composition in the fishing grounds can influence the selective performance of fishing gear. This is not only because environmental factors affect fish behaviour towards fishing gears but also because selective fishing gears can have limitations with regard to fish densities entering it for example.

Success in selectivity trials at sea rely first on a good experimental design. It is important to determine when and where the experiments will be carried out so that the trials represent ordinary fishing conditions. Also, the choice of a sampling method to be used is crucial because it will determine what kind of additional gear one will have to use during the trials. Finally, the choice of a sampling method should be done considering the analytical and practical advantages/disadvantages of each of the available methods.

Different methods for measuring selectivity in towed fishing gears are described in reference [27]. These authors divided the methods into two categories: the Paired-gear method and Covered-gear method. In the Paired-gear method, two gears of equal overall dimensions are towed alternatively or alongside each other. In one of the gears (the test gear), the selectivity device to be tested is installed, whereas the other gear (the control gear) is built in small unselective meshes (**Figure 3**). Thus, the selective properties of the tested device are calculated, assuming that the small mesh size gear captures a size and species composition that is equal to the one that has entered the test gear.

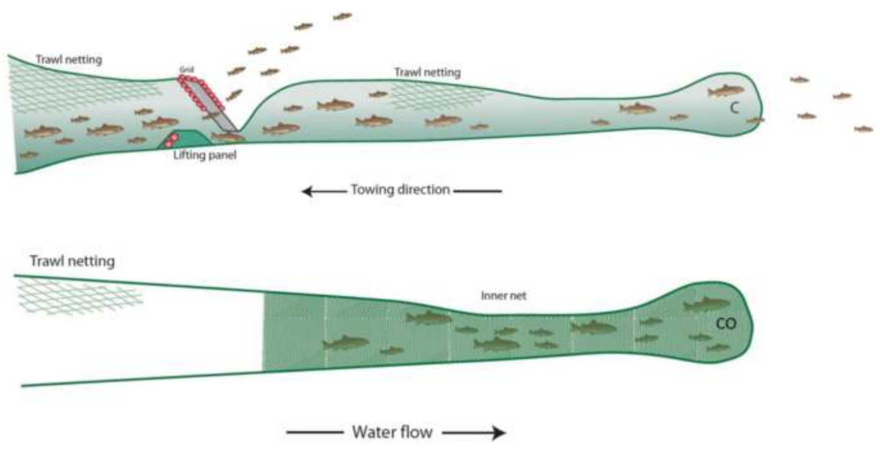


**Figure 3.** Illustration of the Paired-gear method showing the test (above) and the control (below) gear.

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The trouser trawl, twin trawl, parallel haul, and alternate haul methods are examples of the Paired-gear method [27]:

- Trouser trawl method: In a single trawl, the belly is divided into two extension pieces and codends in a way that one of them acts as the control gear and the other one acts as the test gear.
- Twin trawl method: In this case, the gear is composed of two trawls. In one of the trawls, the gear to be tested is installed while the other one is used as control.
- Parallel haul method: In this case, two vessels tow one single trawl each alongside each other. In one of the trawls, the gear to be tested is installed while the other one is used as control.
- Alternate haul method: Here one vessel alternates the use of the test and the control gear.

The covers used in the Covered-gear method can vary a lot in size and shape, depending on the gear they need to cover [24]. The most important properties to look for when choosing a cover are that it needs to cover the selective device completely, it should keep the desired geometry and not be an obstacle for fish escaping through the tested device (avoid masking effect), and it should not (or minimally) reduce water flow. Square mesh covers are therefore most often used to avoid geometry problems and masking of the selective device. Still, measurements of the water flow show that the flow inside codends can be substantially reduced even when using these types of square mesh covers [28].

In the Barents Sea, the compulsory selectivity devices fishermen are allowed to use are composed of a grid section followed by a 130-mm codend. Thus, the selectivity process in the gear is a dual selection process [30] where a selection process in the grid section is followed by a selection process in the codend. To measure the selectivity of such dual selection devices, one can either install a single cover over both devices (**Figure 4**) [11] or install an independent cover over each of the selective devices (**Figure 5**) [29]. The challenge of using independent covers with respect to using a single cover is that there is an additional compartment to be considered and that the practical operations on board with multiple covers can be more challenging.

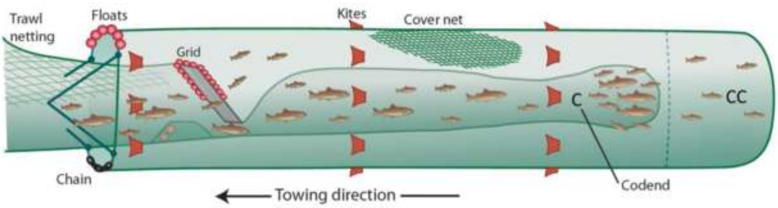


**Figure 4.** Single covered method that covers the grid section and codend.

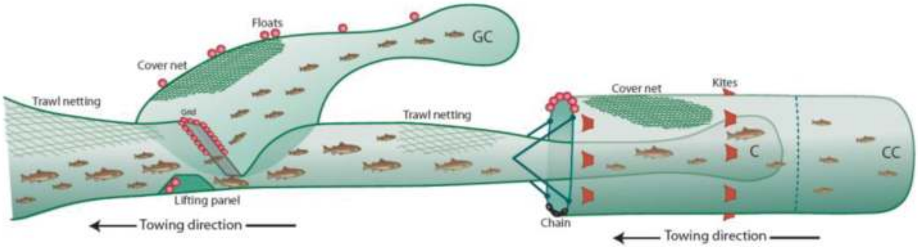


**Figure 5.** Dual cover method.

If the objective of the experiment is to collect selectivity data in order to assess only the size selection in the grid section, then the covered-grid method can be applied (**Figure 6**) [25].

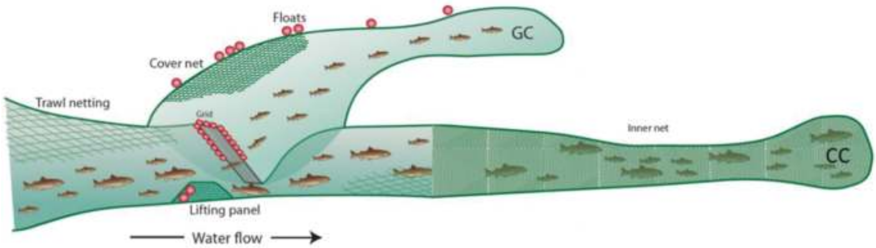


**Figure 6.** The Covered-grid method.

In some experiments, the use of covers can be challenging, for example, they cannot be installed in a way that can guarantee that all escapees are collected, there is limited space on the vessel, etc. In such circumstances, the Paired-gear method is applied.

When carrying out trawl selectivity experiments, it is important that the trials are carried out within a limited period of time and in an area that holds a fairly similar species and size distribution of fish. Large variations in the availability of fish can create loss of precision in the results, whereas large variations in the size distribution of fish can lead to large between-haul variation in the selectivity parameters L50 and SR. Methods like the Covered-gear method, which provides direct information about the fish escaping from the selective device being tested, are more robust regarding variability in both abundance and size distribution of fish. Other methods, like, for example, the alternate haul method, are more sensible to changes in fishing area as one needs to assume that the size and species distribution entering the gear is the same for the test and control hauls carried out.

Measuring the size selective properties of towed fishing gears requires length measuring the fish collected in the different compartments of the gear (test codend and cover(s) or control codend). The number of fish that needs to be caught and length measured to achieve a certain precision in the selectivity results have for years been an issue among fisheries scientists.

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Especially in the cases where the catches exceed the number of fish that can be measured, it is important to know how many fish one should measure and how an eventual subsample should be taken. An ideal subsample is a random sample that represents well the size distribution of the fish in the catch. Normally this subsample is taken from the catch in random batches to avoid potential accumulations of specific sizes of fish that can occur, for example, in the collection bins of the vessels. For each species, the fish in the fraction of the catch that is not length measured needs to be counted to calculate the sampling ratio in the catch.

Diverse sampling strategies in experimental trawl selectivity gear were studied by Millar [34], who concluded that sampling the same number of fish from the different compartments was the most efficient sampling method. Also, how the precision in selectivity results varied depending on the amount of fish caught and length measured with both the Paired-gear and the Covered-gear methods was investigated in reference [35]. The results of the investigation showed that the uncertainty in the selection parameters L50 and SR decreased with increasing number of fish measured, and that this relationship could be described by a power model. The results also demonstrated that the sampling effort needed to achieve a specific uncertainty level for the selection parameters was always lower for the Covered-gear method compared to the Paired-gear method (in many cases the number of fish that would need to be measured to maintain a specific uncertainty level was around 10 times higher for the Paired-gear method than for the Covered-gear method). The results of these studies illustrate again the importance of carrying out proper experimental design before starting the sea trials. Both the potential limitations of the operations that need to be carried out on board and the advantages and disadvantages of the different sampling methods need to be always considered.

For each haul conducted with one of the experimental collection methods described above (**Figures 3–6**), the catch in each compartment (codend, cover(s), control) is length measured species by species. These length measurements are sorted into so-called length classes that in the Barents Sea are typically 1 cm wide. In a dataset, each haul consists of count data that show how many fish of those collected in each of the compartments belong to the same length class. If subsampling is applied only to a proportion of the fish in each compartment, the sampling factor for each compartment is also provided together with the count data. **Table 1** shows an example of a data file resulting from one haul. In this case, the data was collected using the single covered method (**Figure 4**), and 54% of the fish in codend and 62% of the fish in the cover were length measured. The rest of the fish in each compartment was counted. Analysis of such data (**Table 1**) forms the basis for estimating the selectivity of trawl gear by the methods described in the next section.

| Length class (cm) | Number of fish in the codend | Number of fish in the cover |
|---|---|---|
| 25.5 | 0 | 0 |
| 26.5 | 0 | 0 |
| 27.5 | 0 | 0 |
| 28.5 | 0 | 0 |

| Length class (cm) | Number of fish in the codend | Number of fish in the cover |
|---|---|---|
| 29.5 | 0 | 0 |
| 30.5 | 2 | 43 |
| 31.5 | 2 | 23 |
| 32.5 | 3 | 64 |
| 33.5 | 1 | 118 |
| 34.5 | 7 | 116 |
| 35.5 | 5 | 279 |
| 36.5 | 7 | 137 |
| 37.5 | 5 | 179 |
| 38.5 | 10 | 180 |
| 39.5 | 13 | 106 |
| 40.5 | 12 | 266 |
| 41.5 | 2 | 61 |
| 42.5 | 7 | 50 |
| 43.5 | 9 | 52 |
| 44.5 | 12 | 26 |
| 45.5 | 16 | 21 |
| 46.5 | 12 | 61 |
| 47.5 | 14 | 9 |
| 48.5 | 21 | 18 |
| 49.5 | 16 | 8 |
| 50.5 | 26 | 3 |
| 51.5 | 13 | 11 |
| 52.5 | 21 | 0 |
| 53.5 | 10 | 5 |
| 54.5 | 22 | 0 |
| 55.5 | 16 | 1 |
| 56.5 | 11 | 2 |
| 57.5 | 10 | 0 |

| Length class (cm) | Number of fish in the codend | Number of fish in the cover |
|---|---|---|
| 58.5 | 20 | 1 |
| 59.5 | 7 | 0 |
| 60.5 | 9 | 0 |
| 61.5 | 8 | 0 |
| 62.5 | 7 | 0 |
| 63.5 | 5 | 0 |
| 64.5 | 0 | 0 |
| 65.5 | 2 | 0 |
| SAMPLING | 0.54 | 0.62 |

**Table 1.** Illustration of a dataset (one single haul) collected using the covered codend method.

## 5. Methods to estimate size selection parameters

The accepted scientific method for estimation of trawl size selectivity is based on a Maximum Likelihood Estimation (MLE) [27]. The maximization problem this represents is by convenience converted into a minimization problem simply by adding a minus sign in front of the function that else would have been a maximization. Further, to simplify the formulation, the natural logarithm (*ln*) is taken to the function prior to minimization as this leads to a simpler formulation that is easier to minimize. This step is in valid since the *ln* of a function, and the function itself, has the same minimum for the same model parameter values. The function to minimize depends both on the selection system for which the data has been collected and the level of detail intended, and as described in the previous section on which of the experimental data collection has been applied. Conditioned that the size selection model applied in the estimation is able to describe the size selection processes occurring sufficiently well, the MLE estimation provides the model parameters (see Section 3) that make the collected experimental size selection data most likely. If the intention is to assess the combined size selectivity in a single haul *j* based on the covered gear method (**Figure 4**), based on the *logit* model Eq. (1), the following equation is minimized with respect to $L50_j$ and $SR_j$:

$$-\sum_{l}\left\{\begin{array}{l} nc_{jl}\times\ln\left(\dfrac{qc_j\times r_{logit}(l,L50_j,SR_j)}{qc_j\times r_{logit}\left(l,L50_j,SR_j\right)+qcc_j\times\left(1.0-r_{logit}\left(l,L50_j,SR_j\right)\right)}\right)+ncc_{jl} \\ \times\ln\left(\dfrac{qcc_j\times\left(1.0-r_{logit}\left(l,L50_j,SR_j\right)\right)}{qc_j\times r_{logit}\left(l,L50_j,SR_j\right)+qcc_j\times\left(1.0-r_{logit}\left(l,L50_j,SR_j\right)\right)}\right)\end{array}\right\} \tag{6}$$

Where $nc_{jl}$ is the number of fish in length class $l$ that is length measured in the haul $j$ in the codend; and $ncc_{jl}$ is the number of fish in length class $l$ that is length measured in the haul $j$ in the cover. $qc_j$ and $qcc_j$ are the corresponding sampling rates. The summation in Eq. (6) is over length classes $l$.

In case the Paired-gear method (**Figure 3**) is applied for the data collection, the function to minimize would be:

$$-\sum_{l}\left\{\begin{array}{l} nc_{jl}\times\ln\left(\dfrac{qc_j\times SP_j\times r_{logit}(l,L50_j,SR_j)}{qc_j\times SP_j\times r_{logit}\left(l,L50_j,SR_j\right)+qco_j\times\left(1.0-SP_j\right)}\right)+nco_{jl}\times \\ \ln\left(\dfrac{qco_j\times\left(1.0-SP_j\right)}{qc_j\times SP_j\times r_{logit}\left(l,L50_j,SR_j\right)+qco_j\times\left(1.0-SP_j\right)}\right)\end{array}\right\} \tag{7}$$

Compared to Eq. (6), Eq. (7) includes an additional parameter $SP_j$ that needs to be estimated together with $L50_j$ and $SR_j$. $SP_j$ is the so-called split parameter that quantifies the proportion of fish entering the test side of the gear. $nco_{jl}$ is the amount of fish in length class $l$ that is length measured in the control codend and $qco_j$ is the corresponding sampling rate.

Several of the size selection studies carried out in the Barents Sea demersal trawl fishery have applied Eq. (6) or (7) to estimate the combined size selection for individual hauls. In most cases, a mean size selection for the group hauls is subsequently estimated in a second estimation step using the size selection results obtained in the individual hauls and following an estimation procedure described in references [24, 30, 32]. This procedure accounts for both the uncertainty in the estimated size selectivity in the individual hauls (often named within-haul variation) and the between-haul variation in the size selection.

However, in most of the recent studies the dual nature of the size selection process in the gears has been explicitly accounted for by basing the analysis on the dual selection model described by Eq. (5). Further, in most of these studies the final aim has been to estimate the size selection averaged over a group of hauls. Therefore, the process involves summing data over hauls in the estimation process.

If the single covered data collection method (**Figure 4**) is applied, this would lead to minimizing the following equation:

$$-\sum_{j=1}^{m}\sum_{l}\left\{\begin{array}{l}\dfrac{nc_{jl}}{qc_j}\times\ln\left(r_{dual}(l,C_{grid},L50_{grid},SR_{grid},L50_{codend},SR_{codend})\right)+\dfrac{ncc_{jl}}{qcc_j}\times \\ \ln\left(1-r_{dual}(l,C_{grid},L50_{grid},SR_{grid},L50_{codend},SR_{codend})\right)\end{array}\right\} \tag{8}$$

In the case of Eq. (8), the minimization is carried out in five dimensions to estimate $C_{grid}$, $L50_{grid}$, $SR_{grid}$, $L50_{codend}$, and $SR_{codend}$. The outer summation is over the $m$ hauls conducted.

If the Paired-gear data collection method (**Figure 3**) is applied, then the estimation is conducted in six dimensions because the average split *SP* also needs to be estimated. In this case, the function to minimize becomes:

$$-\sum_{j=1}^{m}\sum_{l}\left\{\begin{array}{l}\frac{nc_{jl}}{qc_{j}}\times\ln\left(\frac{SP\times r_{dual}(l,C_{grid},L50_{grid},SR_{grid},L50_{codend},SR_{codend})}{SP\times r_{dual}\left(l,C_{grid},L50_{grid},SR_{grid},L50_{codend},SR_{codend}\right)+1-SP}\right)+\frac{nco_{jl}}{qco_{j}}\\ \times\ln\left(\frac{1-SP}{SP\times r_{dual}\left(l,C_{grid},L50_{grid},SR_{grid},L50_{codend},SR_{codend}\right)+1-SP}\right)\end{array}\right\} \tag{9}$$

If the dual covered data collection method (**Figure 5**) is applied, the precision in estimating the size selection of the gear can be improved. In this case, the equation to be minimized becomes:

$$\sum_{j=1}^{m}\sum_{l}\left\{\begin{array}{l}\frac{ng_{jl}}{qg_{j}}\times\ln\left(1-r_{clogit}\left(l,C_{grid},L50_{grid},SR_{grid}\right)\right)+\frac{ncc_{jl}}{qcc_{j}}\times\\ \ln\left(r_{clogit}\left(l,C_{grid},L50_{grid},SR_{grid}\right)\times\left(1-r_{logit}\left(l,L50_{codend},SR_{codend}\right)\right)\right)+\frac{nc_{jl}}{qc_{j}}\times\\ \ln\left(r_{clogit}\left(l,C_{grid},L50_{grid},SR_{grid}\right)\times r_{logit}\left(l,L50_{codend},SR_{codend}\right)\right)\end{array}\right\} \tag{10}$$

If the only objective is to assess the average size selection in the grid section, then the Covered-grid data collection method (**Figure 6**) can be applied. In this case, the function to minimize will be:

$$\sum_{j=1}^{m}\sum_{l}\left\{\begin{array}{l}\frac{ng_{jl}}{qg_{j}}\times\ln\left(1-r_{clogit}\left(l,C_{grid},L50_{grid},SR_{grid}\right)\right)+\frac{ncc_{jl}}{qcc_{j}}\times\\ \ln\left(r_{clogit}\left(l,C_{grid},L50_{grid},SR_{grid}\right)\right)\end{array}\right\} \tag{11}$$

When estimating the average size selectivity, based on minimizing Eq. (8)–(10) or (11), the uncertainty on the parameters and size selection curve is often estimated using a double bootstrap method as described in references [30, 31, 33].

The ability of a size selection model to describe the experimental size selection data is frequently evaluated based on calculating a *p*-value for model deviance versus the degrees of freedom [31]. This *p*-value quantifies the probability to by coincidence obtain at least as big discrepancy between model and data as observed. Thus, this *p*-value should not be below 0.05 for the model to be able to describe the experimental size selection data well. However, a low *p*-value can also be a result of over-dispersion in the data, which in case of having a low *p*-value should be inspected before rejecting the size selection model.

## 6. The FISHSELECT methodology

FISHSELECT is a framework of methods, tools, and software developed to determine whether or not a fish is able to penetrate a certain mesh [36]. Through computer simulation, FISHSELECT enables the estimation of the selectivity parameters L50 and SR for a certain species and selection device by comparing the morphological characteristics of the former and the shape and size of the latter. This methodology has been successfully used to estimate mesh selectivity of the most relevant demersal fish species in the Barents Sea: cod (*G morhua*), haddock (*M. aeglefinus*), Greenland halibut (*R. hippoglossoides*), and redfish (*Sebastes ssp*.) [31, 37–39]. The results obtained with the application of FISHSELECT have proved the reliability of the method as they are coherent with the results registered from earlier sea trials [37–39]. Thus, if we consider the flexibility the method offers compared to the traditional selectivity measuring methods, the value of the method becomes obvious.

By means of the FISHSELECT tools and software, one can predict the selectivity of a specific fishing gear and species. This can also be achieved with the more traditional selectivity study methods; however, FISHSELECT is unique that once the morphology analyses are carried out for a certain species, one can predict the selectivity of this species for endless mesh shapes (including grids), sizes, and opening angles (OAs). Some of the features or advantages of FISHSELECT with respect to the traditional sea trial selectivity studies are that:

**I.** New estimations do not need additional fieldwork.

**II.** FISHSELECT provides fast answer on the selectivity parameters that can be expected from an eventual change in the gear. In a similar way, if one wishes to change the selection properties of a gear to achieve certain selectivity for a species or multiple species, FISHSELECT can fast predict the changes necessary in the gear to achieve those selectivity objectives.

**III.** The method gives an overall estimation of as many species as one wishes. It is interesting to note that most often the gear will be designed as a compromise on the selective properties of several species [37] that different cleaner-fish species with various body sizes and shapes are harvested at the same time.

**IV.** The results obtained from FISHSELECT can also be used to aid in the interpretation of sea trial selectivity results.

Because FISHSELECT is based on the relationship between fish length and weight, and the shape of the fish's cross-section at different points of its body, factors like the condition of the fish in the different seasons need to be taken into consideration. When collecting the morphological data for a certain species, it is important to cover the whole length spectra for the fish as through its growth not all the body parts grow proportionally. Also, if the fish included in the measurements is captured through different seasons, it would help covering a wider spectra of the different shapes the species can acquire. The wider the spectra of fish covered and the higher the amount of fish included in the measured fish pool, the lower the uncertainty in the predictions.

The application of FISHSELECT is divided into four steps:

*Step 1: morphological data*

In the first step, the fish length (in mm), weight (in g), and its morphology at different cross sections (CSs) need to be measured. The number and position of the CSs taken are different for each fish species, and are decided based on earlier experiences considering the positions likely to determine if a fish will be able to escape through meshes or grids of different sizes and shapes. For fish, in general, three cross sections have been measured per fish [38]. For cod and haddock, for example, these three cross sections were located at the end of the opercula (maximum girth of the head), at the foremost point of the first dorsal fin, and maximum girth of the fish [37]. The cross sections are measured by means of a mechanical sensing tool named morphometer. The morphometer consists of an aluminum frame and measuring aluminum sticks (2.5 mm wide) that can be shifted horizontally and fixed at a desirable position (**Figure 7**). The shape formed in the morphometer is later converted into a digital image using a flatbed scanner. The image resulting from the scanner is finally digitized using the image analysis tools implemented in the FISHSELECT software tool [36].

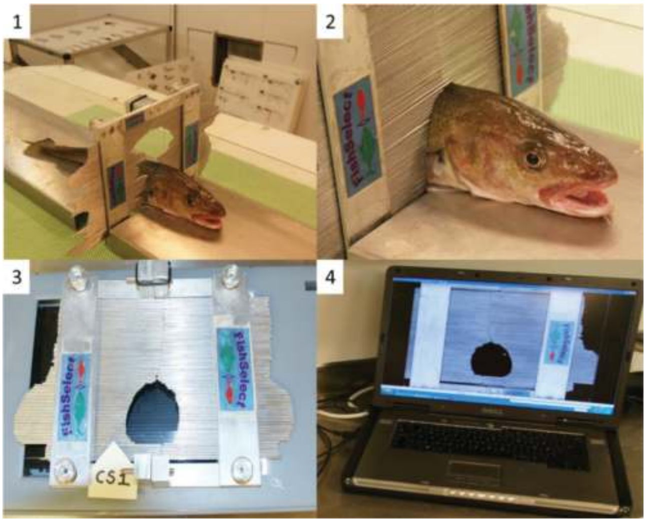


**Figure 7.** Illustration of the use of a morphometer on cod (*Gadus morhua*).

*Step 2: Fall-through experiments*

Fall-through experiments are carried out to decide if a fish can in principle physically pass through a certain rigid shape (subjected to the force of gravity only) (**Figure 8**). These shapes are perforated in 5-mm-thick solid nylon plates [39]. The shapes tested normally include diamonds, hexagons, and rectangles; however, there are no restrictions to the shapes one can test and use in FISHSELECT.

**Figure 8.** Illustration of the fall-through procedure on haddock (*Melanugrammus aeglefinus*). Each interchangeable plate contains a number of different mesh shapes where each fish is tested. All fish included in the study need to be tested in all meshes.

*Step 3: Cross-section modeling*

The CS shapes registered with the morphometer need to be modeled so that they can be further analyzed in FISHSELECT. The software has more than 100 different models available to model each of the different cross sections of the fish (**Figure 9**). One needs to first determine which of the available models seems to represent each of the CSs well enough and later fit all these relevant models to each digitized shape. Each of the models is tested on each of the CSs registered for each fish, and the model with the lowest AIC [40] is chosen for further analysis in FISHSELECT. Once the parameters in the model defining each of the cross sections are the length of the fish, one can create virtual populations with defined CSs.

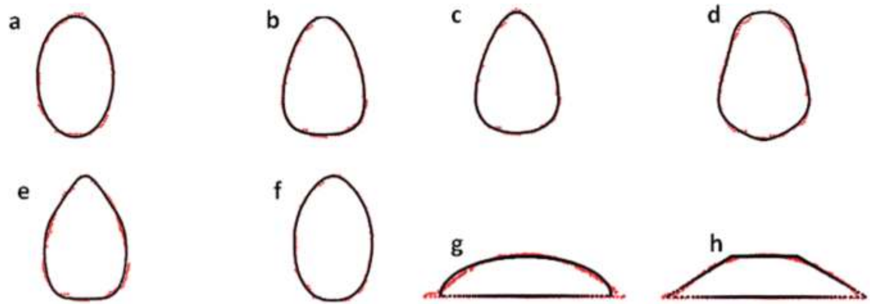


**Figure 9.** Illustration of some of the parametric shapes available in FISHSELECT: Shapes like (a)–(f) are typically used for roundfish while (g)–(h) are normally used on flatfish species.

*Step 4: search for penetration model*

Fish can be compressed both dorsoventrally and laterally. Thus, different compression models need to be tested for each CS as a first step to establish an optimal penetration model for the species tested (**Figure 10**). The optimal penetration model is established by comparing the penetration results of each compression model tested with the fall-through results. The degree of agreement (DA) between the simulated and experimental fall-through results is then used to choose an optimal penetration model (see [36, 37] for the mathematical expression and further information about DA).

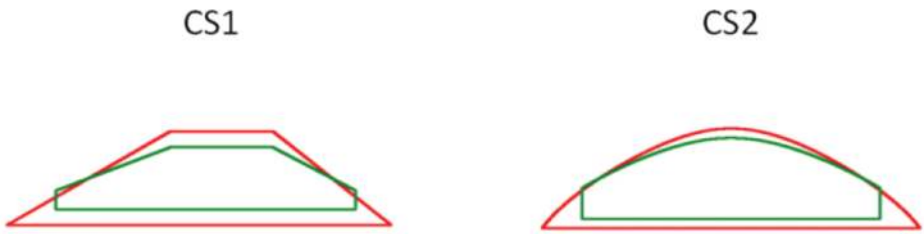


**Figure 10.** Shape of the optimal penetration model (green) overlapped on the original shape modeled from the morphometer (red) for Greenland Halibut (*Reinhardtius hippoglossoides*).

Given virtual populations with the desired population structure and defined CSs and a defined penetration model, the size selective properties of a range of mesh shapes and sizes can be predicted in FISHSELECT by simulation. The outcome of the method consists of L50 and SR estimations for all of the included mesh sizes, shapes, and OAs.

## 7. FISHSELECT results for Northeast Arctic demersal species

Cod, haddock, redfish, and Greenland halibut are the four most important commercial species in the Barents Sea demersal trawl fisheries. FISHSELECT has already been applied to all four species, and the results have in all cases showed to be coherent with the results obtained from earlier sea trials [31, 37–39], . Because the compulsory gear in the Barents Sea demersal trawl fishery is composed of a sorting grid followed by a size selective diamond mesh codend, the FISHSELECT studies present results for both different bar spacing grids and different diamond mesh size codends. **Figure 11** shows selectivity results obtained with the different bar spacing grids for both cod and haddock [37]. **Figure 12** shows the predicted and observed L50 versus mesh size for *Sebastes* spp. **Figure 13** shows historical selectivity results for Greenland halibut compared to FISHSELECT predictions. Finally, **Figure 14** shows the variation in L50 for redfish with varying mesh size and OA for diamond meshes.

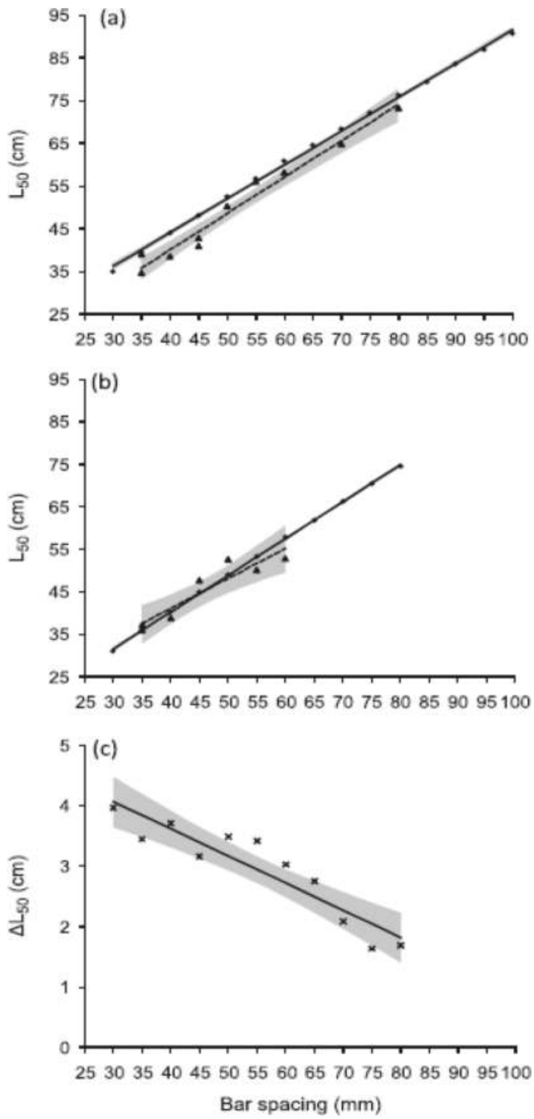


**Figure 11.** Selectivity results obtained with the different bar spacing grids for both cod (*G. morhua*) (a) and haddock (*M. aeglefinus*) (b). The solid line is a trend line fitted to the FISHSELECT results (diamonds), which are presented for up to the maximum fish size included in the data collection process. The broken line is a trend line added to the sea trial selectivity results (triangles) obtained for the different bar spacing grids in [41]. Panel (c) shows the L50 differences and a trend line for these differences between cod and haddock. The gray areas in the three panels represent the 95% confidence limits for the added trend lines. Source: [37].

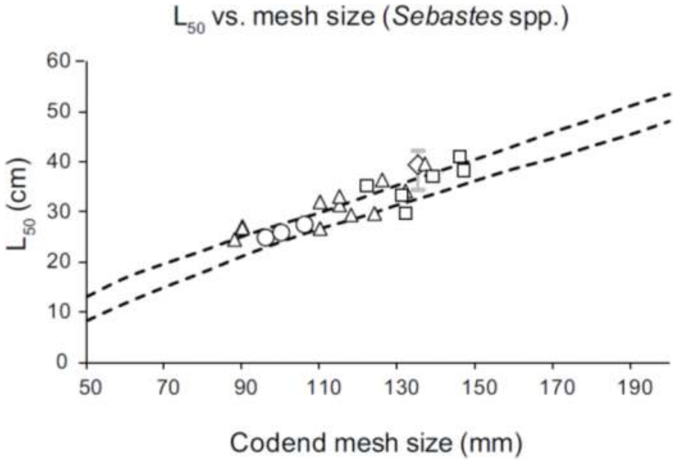


**Figure 12.** Predicted and observed L50 versus mesh size relationships for redfish (*Sebastes* spp.): Predicted band for codend L50 for different mesh sizes based on the FISHSELECT analysis of the data collected for *Sebastes marinus* (stippled curves); new results from sea trials for *S. marinus* (diamonds); previous results for *S. marinus* (squares); previous results for *Sebastes mentella* (triangles) and *Sebastes mentella/faciatus* (circles). Source: [38].

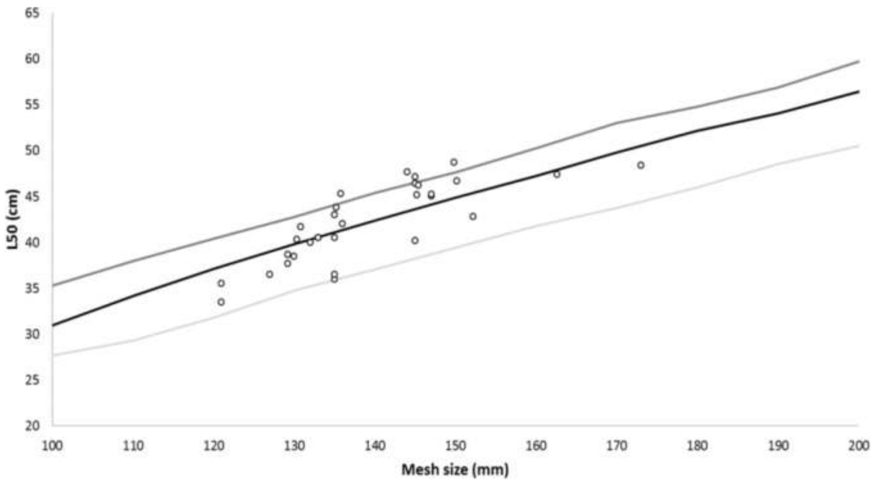


**Figure 13.** Historical data for Greenland halibut (*R. hippoglossoides*) codend selectivity (circular marks) plotted together with FISHSELECT estimations (lines). Source: [39]

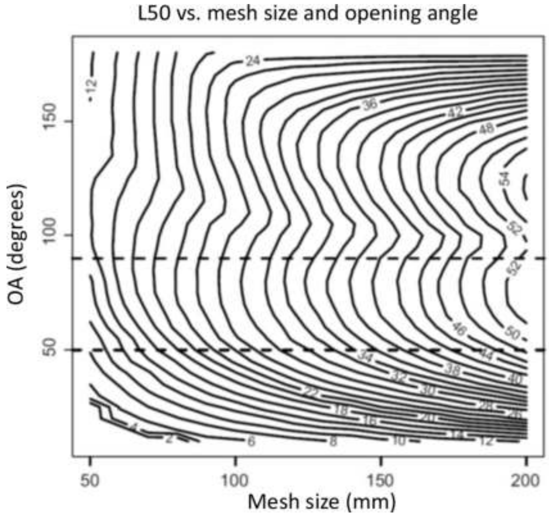


**Figure 14.** Design guide showing the variation in L50 for redfish (*S. marinus*) with varying mesh size and OA for diamond meshes. Source: [38].

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