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# Industry-led fishing gear development under the new European Union Common Fisheries Policy

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# Industry-led fishing gear development under the new European Union Common Fisheries Policy

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# Preface

The present thesis was submitted in partial fulfilment of the requirements for obtaining a Doctor of Philosophy (PhD) degree. The thesis consists of a synopsis and four papers. When submitted the thesis, one paper was published, one was in revision, one submitted and one was a manuscript.

The work took place at the Technical University of Denmark – National Institute of Aquatic Resources (DTU Aqua), section for Ecosystem based marine management, in the fisheries technology group based in Hirtshals from December 2015 to April 2019. Moreover, I wish to express my sincere gratitude to my supervisors Ludvig A. Krag and Jordan P. Feekings, their contributions to this thesis, support and guidance throughout my PhD were of great value to me.

Further I wish to thank:

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Hirtshals, April 2019

Tiago Alexandre Matias da Veiga Malta

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**Paper 2**: Veiga-Malta, T., Feekings, J., Herrmann, B., Krag, L.A., Accepted under condition to review. Industry-led fishing gear development: Can it facilitate the process?. Resubmitted revised version for review

**Paper 3**: Veiga-Malta*, T., Breddermann*, K., Feekings, J.P., Krag, L. A., Paschen, M. Submitted. Understanding the hydrodynamics of a size sorting grid in a crustacean fishery. Submitted

(*) These authors contributed equally to this work

**Paper 4**: Veiga-Malta, T., Feekings, J., Frandsen, R.P., Herrmann, B., Krag, L.A. Testing a size sorting grid in the brown shrimp (*Crangon crangon* Linnaeus, 1758) beam trawl fishery. Manuscript

## Dansk resumé (Abstract in Danish)

Reformen af EU´s fælles fiskeripolitik og implementering af landingsforpligtelsen har, mere end nogensinde før, øget vigtigheden af at fiskeindustrien kan tilpasse selektiviteten af redskaberne for at opnå optimal afkast i fiskeriet. Dette skyldes skiftet til et forvaltningssystem der er fangstbaseret frem for landingsbaseret, og hvor uønsket fangst af regulerede arter skal landes og modregnes kvoten. Eftersom mængden af den uønskede fangst varierer afhængigt af det anvendte fiskeredskab, området, årstiden, fiskepraksis og kvotesammensætning, vil det desuden være vigtigt at kunne tilpasse selektiviteten på det enkelte fartøj. Til forskel fra i dag hvor antallet af tilladte redskaber er meget begrænset, kræver dette system derfor at der er et større antal specialiserede fiskeredskaber tilgængelige for de forskellige fiskerier. En så omfattende udvikling og afprøvning af selektive redskaber er svær at gennemføre under den traditionelle proces for redskabsudvikling under det nuværende fiskeriforvaltningssystem i EU. Dette studie undersøger derfor potentialet i en industristyret proces, der dels kan identificere fiskerier med problematiske fangstsammensætninger, og dels kan udvikle og afprøve redskabsløsninger som kan indgå i en værktøjskasse af mere specialiserede redskaber. En industristyret redskabsudvikling åbner mulighed for at køre flere parallelle forsøg samtidig med at der gennemføres en grundig kommerciel udvikling og afprøvning inden de omkostningstunge videnskabelige forsøg. Når flere redskaber udvikles og afprøves parallelt er det desuden hurtigere at udvælge de mest lovende. Studiet har belyst de mest afgørende trin i en industristyret redskabsudvikling såsom muligheden for at industrien selv indsamler selektionsdata samt hvilken type redskaber en sådan proces er i stand til at udvikle.

Paper 1: Baseret på simulerede data undersøges det om industrien selv kan indsamle længdedata på fisk, i en sådan kvalitet, at de kan anvendes til at estimere det nye redskabs selektive egenskaber sammenlignet med et standard redskab. Industriens evne til at indsamle disse data er essentielle for at kunne foretage en hurtig udvælgelse af de mest lovende redskabsløsninger. Resultaterne viser at det kun kræver en relativt lille prøvestørrelse (500-1000 individer) at evaluere

et redskabs selektive egenskaber for den pågældende art. Det er således muligt for industrien at indsamle de nødvendige data uden at hovedaktiviteten ombord, det kommercielle fiskeri, påvirkes.

Paper 2 præsenterer et studie hvor industrien udviklede en trawlpose til det demersale fiskeri efter torsk (*Gadus morhua*) i Østersøen. Under udviklingen af redskabet kunne industrien på én og samme gang modificere flere dele af redskabet i arbejdet på at opnå det ønskede resultat. Resultaterne viser at industrien var i stand til at udvikle et velfungerende redskab. Imidlertid blev der foretaget adskillige ændringer på redskabet uden hensyntagen til at nogle af ændringerne havde modsatrettet effekt. En løbende involvering af forskere i udviklingsprocessen er vigtig for at undgå at der laves unødvendige, eller, som i dette tilfælde, modsatrettede ændringer i redskabet.

Paper 3 præsenterer et studie hvor hydrodynamikken i forskellige varianter af sorteringsriste med en lille tremmeafstand på 6 mm undersøges. Dette studie blev gennemført i en vindtunnel hvor vind blev brugt som en proxy for vand. Parametre som form og bredde af tremmerne, ristens vinkel og vindhastigheden blev testet for at identificere hvilke parametre der påvirker hydrodynamikken af risten. Resultaterne viste at porøsitet, vinkel og formen af ristens tremmer påvirkede dens hydrodynamiske egenskaber. Studiet viser desuden at riste, der designes eller monteres forkert, kan have ringe hydrodynamiske egenskaber og således forringe de selektive egenskaber under fiskeriet.

Paper 4 præsenterer et videnskabeligt forsøgsfiskeri med en rist i fiskeriet efter hesterejer (*Crangon crangon*). Tremmeafstanden er 6 mm og designet er baseret på viden indhentet i en hydrodynamisk undersøgelse af en rist. Resultaterne fra forsøgsfiskeriet viste at risten var velegnet til at lukke små rejer ud af redskabet. Kombinationen af en rist med fangstpose lavet af 22 mm diamantmasker opnåede en estimeret L50 på 44,9 mm og en SR på 15,6 mm og det blev demonstreret at redskabet kan bruges som et potentielt alternativ til en 26 mm fangstpose.

# Abstract

With the reform of the European Union (EU) Common Fisheries Policy and the implementation of the Landing Obligation the ability of the fishing industry to adjust the selectivity of their gears is more than ever important in determining the revenue of fisheries. This is due to the change from landings- to catch-based fisheries management, where unwanted catches of regulated species now have to be landed and counted against the quota. Moreover, as the quantity and composition of unwanted catch varies with type of fishing gear used, fishing areas, season, fishing practice and quota availability, changes to the selectivity of the gears will be needed at the vessel level. This implies that a larger number of specialized selective gears need to be available to the different fisheries. Such an extensive development and testing of selective gears is difficult to achieve under the traditional process for gear development under the current EU fisheries management system. Therefore, this study investigates the potential of an industry-led process for identifying issues, and for development and testing of gear solutions as a way to provide the necessary tool-box of more specialized gears. Having industry lead the gear development process allows testing numerous fishing gears in parallel, as well as establishing a real commercial development and testing phase prior to expensive scientific trials. Moreover, this parallel development of different gear solutions allows for quickly filtering the most promising ones. Key steps of such an industry-led gear development process were investigated during this study, such as the possibility for industry to collect selectivity data on the gears tested, or what type of gears can this process produce. This PhD thesis consists of a synopsis and four papers.

Paper 1 investigates, based on simulated data, if the industry can collect length measurement data with enough quality to correctly evaluate the relative selective performance of a new gear compared to a standard gear. The ability of the industry to collect data on the selective performance of a gear is essential to enable a fast identification of the most promising gear solutions, worth scientific investigation. The results show that with relatively small sample sizes (500 to 1000 individuals) it is possible to correctly evaluate the performance of a gear for a given

species. Thus, it is possible for the industry to collect the necessary length based data without affecting their main activity, commercial fishing.

Paper 2 presents a case study where a codend, with several modifications, was developed by the industry for the Baltic Sea demersal trawl fishery targeting cod (*Gadus morhua*). During the development of a fishing gear, the industry can modify several aspects of the gear simultaneously to achieve their goal. The results show that the industry can successfully develop gears to meet their objectives. However, several modifications were made to the gear, without considering that some of those had opposing effects. Therefore, an early and continuous involvement of scientists in the process is crucial to ensure that unnecessary or adverse modifications are not made to the gear.

Paper 3 investigates the hydrodynamics of different variations of a size-sorting grid with a small bar spacing of 6 mm proposed by the industry. This study was conducted in a wind tunnel facility where wind was used as a proxy for water flow. Parameters such bars shape, bars width, grid angle and wind velocity were tested, aiming at identifying which parameters affect the hydrodynamics of the grid. Porosity, angle and the shape of the bars of a grid were found to affect its hydrodynamic performance. The study shows that grids designed and mounted incorrectly can have poor hydrodynamic performances, thus potentially affecting their selective performance during the fishing process.

Paper 4 presents the scientific testing at sea of a size-sorting grid for brown shrimp (*Crangon crangon*) with a small bar spacing of 6 mm, adjusted on the basis of the knowledge obtained from the previous study on the hydrodynamics of the grid. The results showed that the grid successfully allowed for the escape of small shrimp. Moreover, the combination of the grid and a 22 mm diamond mesh codend obtained an estimated L50 of 44.9 mm and a selection range of 15.6 mm, and it was showed that it can be a potential alternative to the 26 mm diamond mesh codend

# 1 Introduction

## 1.1 Global shift from land-based to catch-based fisheries management

### 1.1.1 Discards: definition, impacts and reasons to discard

In commercial fisheries, discards are defined as the "*portion of the total organic material of animal origin in the catch, which is thrown away, or dumped at sea for whatever reason. It does not include plant materials and post-harvest waste such as offal. The discards may be dead, or alive*." (Pérez Roda *et al*., 2019).

Between 2010 and 2014, the average global annual discards were estimated to be 9.1 million tonnes, which represents 10.8% of the global fisheries average annual landings for the same period (Pérez Roda *et al*., 2019). These numbers are of concern considering that a large fraction of the discarded individuals, including commercially important species, does not survive (Yergey *et al*., 2012; Morfin *et al*., 2017; Mérillet *et al*., 2018; Runde and Buckel, 2018; Tsagarakis *et al*., 2018). Discarding has several negative impacts on the ecosystem, with consequences on its biodiversity and functioning (Alverson *et al*., 1994; Votier *et al*., 2010; Suuronen *et al*., 2012; Lent and Squires, 2017; Gray and Kennelly, 2018). Moreover, discarding is a waste of natural resources and it can have economic repercussions for the fishing industry such as decreasing the productivity of fish stocks (Pascoe, 1997; EC, 2007; Diamond and Beukers-Stewart, 2011). Furthermore, discarding at sea adds uncertainty to stock assessments since this portion of the catch is usually poorly documented, thus making it more difficult to accurately estimate fishing mortality (Condie *et al*., 2014). While discarding can be viewed as a way for fishermen to adjust their landings to the legal and market constraints (Eliasen *et al*., 2013; Catchpole *et al*., 2014), the act of discarding and its associated ethical, ecological and economic issues need to be addressed (EC, 2007; Diamond and Beukers-Stewart, 2011; Rochet *et al*., 2014).

There are several identified factors that can determine the amount of discards (Rochet and Trenkel, 2005; Feekings *et al*., 2012; Catchpole *et al*., 2014; Eliasen *et al*., 2013; Damalas *et al*., 2015; van Putten *et al*., 2019), including:

- technical (e.g. selectivity of the fishing gear used, vessel characteristics, and the fishing process),
- legal (e.g. quota limitations, minimum landing sizes (MLS) or Minimum Conservation Reference Size (MCRS), and mismatch between technical regulations and stock structures),
- biological (e.g. species composition, and recruitment period),
- environmental (e.g. weather conditions, spatial heterogeneity in depths and bottom types),
- economic (e.g. market prices fluctuations, low market price, and high grading), and
- social (e.g. fishing community, lack of agreement or understanding of the regulations, and fishermen's perception of discards).

This thesis focuses on the technical factors affecting both the unwanted (discards) and wanted portions of catches, and specifically improving the selectivity of the fishing gears used.

### 1.1.2 Catch-based fisheries management and discard bans

With the acknowledgement of discarding and its associated negativities, together with fisheries management moving towards more ecosystem-based approaches, there has been a global shift from landings-based to catch-based management (Karp *et al*., 2019). Under a catch-based fisheries management system there is a need for documenting the entire catch, including the unwanted portion, to be able to correctly estimate the mortality levels associated with fishing activities (Borges, 2018). One of the most common ways to address this need for documenting the entire catch is through the prohibition to discard unwanted catches (Condie *et al*., 2014; Karp *et al*., 2019). Moreover, by making the unwanted catch count against the quota and therefore coupling the selectivity of a fishery with its economy, a catch-based system aims at creating strong economic incentives for fishermen to avoid this unwanted catch and thus become more selective in their fishing practices (Condie *et al*., 2014; ICES, 2018; O'Neill *et al*., 2019; Reid *et al*., 2019). Thus, catch-based management can potentially create new and strong incentives for the industry to improve the overall selectivity of fisheries because it is now in fishermen's interest to reduce unwanted catch in the first place (Karp *et al*., 2019). The use of more selective fishing gears is an obvious way to improve the selectivity of a fishery, although changing fishing tactics or introducing temporal and spatial closures can also reduce unwanted catches (Bellido *et al*., 2019; O'Neill *et al*., 2019; Reid *et al*., 2019). Nevertheless, this incentive to improve the fishery can only be effective if there is a proper monitoring, control and enforcement of the fisheries (Bellido *et al*., 2011; Kindt-Larsen *et al*., 2011; Karp *et al*., 2019, Kraak and Hart, 2019).

Several countries have implemented discard bans in their fisheries, including United States of America (USA), Canada, Chile, Argentina, New Zealand, Iceland, Norway, Faroe Islands and India (Condie *et al*., 2014; Borges *et al*., 2016; Karp *et al*., 2019). The different discard bans have different levels of complexity and enforcement as well as different levels of success. For example, in the USA, since 1998, a discard ban for Pacific cod (*Gadus macrocephalus*) and walleye pollock (*Gadus chalcogrammus*) has been in place in the Alaska groundfish fishery, supported by a highly comprehensive observer program (Condie *et al*., 2014; Karp *et al*., 2019). This discard ban has been described as highly successful at reducing the discards levels of the targeted species (Condie *et al*., 2014; Karp *et al*., 2019). In Norway, a discard ban started in 1987 to protect cod and has since evolved to include 55 commercially important species (Gullestad *et al*., 2015; Borges *et al*., 2016; Karp *et al*., 2019). The Norwegian discard ban has been coupled with additional technical measures such as gear specifications to ensure a minimum selectivity, real-time closures, and monitoring and control measures to minimise unwanted catches (Gullestad *et al*., 2015). The recovery of the cod and haddock (*Melanogrammus aeglefinus*) stocks has been associated to the overall combined effect of the different discard management measures. However, as to which measures had the strongest effects is difficult to quantify due to ineffective monitoring and a lack of data (Condie *et al*., 2014; Borges *et al*., 2016). In the case of Chile, a discard ban was implemented in 2001 for all species (commercial and non-commercial) caught. In an attempt to ensure compliance, it was coupled with heavy sanctions for non-compliance, such as deductions of 30% of a fisherman's Individual Transferable Quotas (ITQ; Borges *et al*., 2016; Karp *et al*., 2019). These heavy sanctions, together with an insufficient enforcement, led to an overall non-compliance from the fishermen and discarding continued as normal (Borges *et al*., 2016). In 2012, the legislation was revised and stopped including all species in the discard ban and allowed for exemptions conditional on a minimum 2-year at-sea monitoring and research programme with observers on-board commercial vessels (Borges *et al*., 2016; Karp *et al*., 2019). On the other hand, this revision included provisions for compulsory electronic monitoring on-board fishing vessels; and stronger sanctions for discard offences. As it is still being implemented, it is currently not possible to assess the success of the Chilean discard ban (Karp *et al*., 2019).

The different examples described above highlight key factors for an effective implementation of discard bans: to ensure compliance, high levels of monitoring and enforcement are required (Branch and Hilborn, 2008; Karp *et al*., 2019; Borges and Penas Lado, 2019); additional management measures, which can incentivise for more selective fishing can discourage discarding are needed (Hall and Mainprize, 2005; Stockhausen *et al*., 2012); measures that prevent unwanted catch should be prioritized (Condie *et al*., 2014; Salomon *et al*., 2014); and flexibility within gear-based technical regulations is essential to decrease unwanted catches without making the fisheries economically unviable (Condie *et al*., 2014; Eliasen *et al*., 2019).

## 1.2 Landing Obligation: the European Union's discard ban

In the European Union (EU), fisheries of all member states are managed through the Common Fisheries Policy (CFP; EU, 2013). This legislation was first established in 1983 and sets overall objectives for the EU fisheries while aiming at preserving economic, social and environmental principles in fisheries management (Salomon *et al*., 2014; Borges, 2018). Since it was established, the CFP has been reviewed every ten years and has been subjected to three reforms (EC, 2009; Salomon *et al*., 2014; Borges, 2018).

In 2013, the new reform of the EU CFP was finalized following the general concerns raised in the previous years, and its implementation phased in since the 1st of January 2015 (EU, 2013). In this reform, several measures were proposed to adapt European fisheries policies to a more ecosystem-based management, while keeping quotas as its central instrument for achieving stock conservation objectives (Borges, 2018). For example, the reform emphasised the importance of multiannual plans, including several stocks if exploited together, by declaring that they should have priority over the regular annual plans (Salomon *et al*., 2014). Regional groups were also proposed in the new reform as a way to facilitate the management of the marine waters shared by member states by increasing flexibility in decision making and incorporating all stakeholders in the process (Salomon *et al*., 2014; Eliasen *et al*., 2019). Another major change in the reformed CFP, and probably the one with the largest potential impact to the fishing industry, was the introduction of a discard ban, and subsequence change to a catch-based management, in the European fisheries, referred to as the Landing Obligation (LO).

### 1.2.1 Implementation of the Landing Obligation

The introduction of the LO has resulted in an increasing pressure on the fishing industry to eliminate or considerably decrease discards. This regulation aims to eliminate the discarding of all commercial species subject to TAC limits in EU marine waters, as well as species targeted by effort regulated fisheries in the Mediterranean for which a MLS has been defined (EU, 2013). For those species, Minimum Conservation Reference Sizes (MCRS) were established using the previous legal MLS as reference values, along with the prohibition to sell catches below the MCRSs for direct human consumption (EU, 2013). The LO was implemented progressively by species and fisheries, starting with pelagic fisheries and fisheries in the Baltic Sea in 2015, and from 1st January 2019, the LO was fully implemented in all European Union fisheries as planned in the reformed CFP (EU, 2013).

The LO, like the other discard bans, does not prohibit all discarding since it only applies to selected commercial species (Borges *et al*., 2016). Moreover, aiming at increasing the flexibility of the LO and thus hoping to facilitate its implementation, the new LO includes four types of exemptions (EU, 2013; Catchpole *et al*., 2017): species for which fishing is prohibited (e.g. endangered and protected species), species that have scientifically demonstrated high survival rates after being discarded, catches damaged by predators, and catches which fall under the *de minimis* exemption. A fishery can obtain *de minimis* exemption, which permits discarding of a predefined portion of the total annual catch, under the premise that selectivity increases are difficult to achieve or that handling of unwanted catches creates disproportionate costs (Catchpole *et al*., 2017, Karp *et al*., 2019). This exemption should be used as a "last resort" mechanism and not without first fully exploring other technical or tactical measures (Karp *et al*., 2019).

### 1.2.2 Fisheries expected to be most affected by the Landing Obligation

Depending on the complexity of a fishery's catch composition (i.e. single-species or mixed-species fisheries) and/or discard ratios, fisheries within EU are challenged by the LO in different ways. The LO is not expected to be of great concern in fisheries such as pelagic fisheries where discard ratios are relatively low (de Vos *et al*., 2016), although discards in volume can be large for these fisheries (Pérez Roda *et al*., 2019). On the other hand, for more complex fisheries such as demersal mixed-species trawl fisheries, it has already proven to be highly problematic (de Vos *et al*., 2016; Catchpole *et al*., 2017; Fitzpatrick *et al*., 2019). The two main issues with these fisheries are i) the filling of quotas with unwanted catch, e.g. catch below the MCRS, leading to considerable economic losses (Prellezo *et al*., 2017); and ii) choke species, i.e. species with the lowest quota in a mixed-fishery, which can lead to an early closure of the fishery while there is still unfished quota of other species (Schrope, 2010; Baudron and Fernandes, 2015). Additionally, handling time and storage space on-board have also become issues under the LO, particularly for small scale fisheries as a result of having to sort and store the catch that would have previously been discarded (Veiga *et al*., 2016; Fitzpatrick *et al*., 2019).

### 1.2.3 Increased difficulty for effective monitoring and control

The LO is a comprehensive legislation for the EU fisheries which impacts a wide range of fisheries and stakeholders throughout Europe, hence stakeholder's participation and acceptance are crucial for the success of the LO (Condie *et al*., 2014, Karp *et al*., 2019). However, the objectives and implementation process of the LO are poorly understood and its legitimacy questioned by the fishing industry, which created additional difficulties in the implementation process (de Vos *et al*., 2016; Catchpole *et al*., 2017). Furthermore, the top-down nature of the CFP, through a micro-management approach, leads to more complex management regulations at the single fisheries level, which goes against the overarching objectives of the 2013 CFP for a simpler, more flexible and regionalized management framework (Fitzpatrick *et al*., 2019). This increase in complexity in the legislation also creates difficulties for the implementation of the LO, since it increases the difficulty for effective monitoring and control.

The quality of the monitoring and control of the fisheries is essential for effective fisheries management, especially under catch-based management systems such as the LO where unwanted catches are counted against the quotas (Suuronen and Sardá, 2007a; Condie *et al*., 2014; Borges *et al*., 2016; Catchpole *et al*., 2017; Borges and Penas Lado, 2019). Not only does the credibility of the policy depend on effective enforcement, but also its expected positive effects will only take effect if adequate monitoring takes place (Borges and Penas Lado, 2019). Poor monitoring and control of a discard ban may lead to increased discards, particularly when coupled with management measures that strongly limit fishing activity and incentivize discarding by counting unwanted catches as part of the quotas (Borges *et al*., 2016). A potential negative consequence of the continuation to discard under the LO is the increased fishing mortality. This higher mortality associated with fisheries may occur as a result of the higher yearly quotas (quota top-ups), since quotas under the LO account for total catches (landings + unwanted catch; Borges, 2018). In recognition of the need for better at sea monitoring, remote electronic monitoring (REM) system have gained attention in recent years as a way to achieve more comprehensive monitoring of the fisheries (Kindt-Larsen *et al*., 2011; Stanley *et al*., 2011; van Helmond *et al.*, 2014; Mangi *et al*., 2015; Needle *et al*., 2015). REM systems have the potential to ensure that catches of all regulated species can be fully monitored at sea and weights of such catches accurately recorded. Moreover, effective monitoring and control of the fisheries can be extremely difficult to achieve, particularly in the case of EU where there is a large diversity of fisheries, including mixed-species fisheries, and management measures (Suuronen and Sardá, 2007a; Veiga *et al*., 2016). For example, even though EU fisheries are regulated by the CFP, each Member State defines their own quota management system and can impose additional regulations for its waters and fisheries, adding complexity to the EU management system (Veiga *et al*., 2016). Nevertheless, effective monitoring and control of the LO should encourage fishermen to increase the selectivity of their fisheries and comply with the regulations (Condie *et al*., 2014; Borges and Penas Lado, 2019).

## 1.3 ´One gear does not fit all´: Industry-led trials for higher flexibility

### 1.3.1 The need for more fishing gear solutions for the industry

The species and/or size composition of the unwanted catch varies between fishing areas and fishing gear used (Murawski, 1996; Feekings *et al*., 2012; Pennino *et al*., 2014). Hence, fishermen under the LO need to be able to adjust the selectivity of their gears to address the different issues arising under this new legislation if they want to maintain the economic sustainability of their fisheries (Condie *et al*., 2014; Eliasen *et al*., 2019; O'Neill *et al*., 2019). This means that a large number of more specific fishing gear solutions need to be available to the fishermen at the regional and fisheries level (Catchpole *et al*., 2017; O'Neill *et al*., 2019). Furthermore, the composition of unwanted catch can vary at the vessel and haul levels according to season and fishing ground (Feekings *et al*., 2012; O'Neill *et al*., 2019). Thus, fishermen will also need to be able to adapt relatively fast to different catch compositions, possibly without having to go to land (O'Neill *et al*., 2019). This extra layer of flexibility can be achieved by developing simple and easily adjustable gear solutions that can be deployed at the haul level (e.g. Melli *et al*., 2018).

### 1.3.2 Higher flexibility in technical regulations

Technical regulations are a set of legal rules that manage where, when and how fishermen can fish (EC, 2016). The objective of technical regulations is to regulate the total amount of biomass removed from commercial stocks and what fishing effort levels can be applied, while minimizing the impacts of fishing on the ecosystem. In the case of the EU, they are established for the majority of the fisheries, but the types of technical regulations differ considerably from fishery to fishery. According to the European Commission, technical measures can be grouped into five major categories (EC, 2016): i) measures that regulate the operation of the fishing gear; ii) measures that regulate the design characteristics of the fishing gears that are deployed; iii) minimum conservation reference sizes (MCRS); iv) measures that set spatial and temporal controls; and v) measures that mitigate the impacts of fishing gears on sensitive species.

For some of the technical regulations, the overall aim is to obtain high and sustainable yields in the fisheries. For example, the definition of mesh sizes and MCRS to reduce the capture of juvenile fish, and in turn minimize the negative impacts of fisheries on stocks (Catchpole *et al*., 2014). However, these regulations can also cause an increase of discards in a fishery, especially in mixed-species fisheries (Catchpole *et al*., 2014). Other technical regulations focus more on reducing bycatch, discards and overall impacts on the ecosystem. Spatial and temporal closures, e.g. marine protected areas, real-time closures or seasonal closures, can be used to protect juveniles, important spawning and foraging areas, and migratory pathways (Little *et al*., 2015; Pérez Roda *et al*., 2019). These measures can reduce discards by simply avoiding the spatial and temporal overlap of fishing effort and unwanted catch. However, if the impacts of the implementation of such closures are not fully assessed, it may lead to an increase of discards and other unexpected effects due to the reallocation of fishing effort (Suuronen *et al*., 2010). Furthermore, technical regulations directly pertaining to the fishing gear used can be found in the majority of the categories mentioned above. Therefore, developing fishing gears that enable fishermen to comply with the different regulations, while maintaining a profitable activity, is of the utmost importance.

Under the current EU management system, the number of gear solutions needed to achieve the necessary flexibility is larger than the one currently available to fishermen, where only a couple of generic gears are legislated for each gear type and area (Eliasen *et al*., 2019). Indeed, the "one gear fits all" type of legislation is the opposite of what is needed under the LO (Condie *et al*., 2014; O'Neill *et al*., 2019). Under this type of technical legislation, only few generic gears are legally allowed at a regional or fishery level, thus fishermen have none to very few options for adjusting the selectivity of their fisheries when needed. Moreover, the current EU management system is often slow and inflexible, where few fishing gear solutions are tested and new gears take several years to be implemented in legislation (Eliasen *et al*., 2019). This rigidness of the system can be a serious barrier when trying to increase the number of gear solutions available for use. The European Commission has also highlighted this inflexibility of the system as a major shortcoming of the current regulation (EC, 2016). Furthermore, a stronger cooperation between fishing industry and scientists has been suggested as a way to facilitate the development of the needed number of gear solutions (Eliasen *et al*., 2019; O'Neill *et al*., 2019). Indeed, the fishing industry's role in the development, testing and implementation of fishing gears has increased in the EU since the 2013 CFP (ICES, 2018). This need for increased collaboration has also been mentioned in the proposal for a new technical measures regulation (EC, 2016). Moreover, to be able to successfully implement the LO, while minimizing the negative economic impacts of landing unwanted catch, a higher flexibility is needed in the technical regulations of fishing gears to facilitate the fishermen's ability to improve the selectivity of their fisheries (EC, 2016; Eliasen *et al*., 2019; O'Neill *et al*., 2019). Indeed, as the quantity of unwanted catch varies with the gear used, fishing areas, seasons, fishing practice and quota availability (Murawski, 1996; Feekings *et al*., 2012; Pennino *et al*., 2014), changes to the selectivity of the gears will need to be implemented at the vessel and haul levels (Melli *et al*., 2018; O'Neill *et al*., 2019).

Taking into account the 2013 CFP reform and recognising limitations of the present technical regulation, the European Commission (EC) proposed in 2016 a new framework for a new technical measures regulation to facilitate the introduction of new mechanisms to increase selectivity under the LO (EC, 2016; Borges and Penas Lado, 2019). In the proposal, the main issues with the current technical regulation are highlighted and three alternative options aiming at address these issues are proposed. The main objectives of the three options proposed are to introduce greater flexibility in the management framework through regional groups, e.g. The Baltic Sea Fisheries Forum (BALTFISH) and the North Sea Scheveningen Group; increase stakeholder involvement in the decision making process; and simplify the current rules (EC, 2016; Eliasen *et al*., 2019).

The preferred option, known as the “Framework Approach” is considered the one that best meets the objectives set by the reformed CFP by linking the current technical regulation to the regional multi-annual management plans, designed by the regional groups (EC, 2016; Eliasen *et al*., 2019). This means that, despite all fisheries still being under the same CFP rules, regional groups would be able to implement specific technical measures (e.g. new fishing gears) to each of the regions. Therefore, the flexibility in the technical regulation needed to better adapt to the challenges associated with the LO would be increased by changing the current technical regulation with the proposed “Framework Approach”. Presently, the proposed new technical regulation is being discussed in the EU and, if implemented, it provides opportunities for a faster and more inclusive development and testing of fishing gears, and a faster political acceptance of new and/or modified gears (Eliasen *et al*., 2019).

### 1.3.3 Industry-led gear development for testing numerous fishing gears

A large diversity of specific fishing gears solutions have to be available to the fishermen, to ensure that they can adapt to the different issues arising under the LO (Catchpole *et al*., 2017; O’Neill *et al*., 2019). However, that is not possible under the current EU fisheries management system that uses a “one gear fits all” approach (Condie *et al*., 2014; O’Neill *et al*., 2019). Furthermore, in order for the industry to solve the issues at hand without losing substantial income, the specific issues arising in the fisheries need to be quickly identified and gear solutions for those issues developed, tested and implemented in a relatively short period (Eliasen *et al*., 2019; Fitzpatrick *et al*., 2019).

To achieve the required flexibility, a greater number of new gears or modifications to existing gears have to be adequately developed, tested, and their selective performance correctly documented for a possible implementation in the legislation (Eliasen *et al*., 2019). This is something difficult to achieve under the traditional process for gear development. Therefore, having the industry not only identifying the problems but developing and testing the gear solutions themselves can potentially facilitate this process, while reducing the economic and time outlay associated with the development of fishing gears. A greater involvement of the industry in the development of gear solutions is something that has also been proposed in the EC proposal for new technical measures regulation (EC, 2016). Moreover, the involvement of industry in gear selectivity projects has previously been shown to provide valuable experience-based knowledge and improve the uptake of the technical measures developed (McCay *et al*., 2006; Johnson and van Densen 2007; Armstrong *et al*., 2013). A way to maximize these advantages is to have the industry lead the gear development and testing process rather than just being involved in it (ICES, 2018).

# 2 Aims of the thesis

In this PhD thesis, the possibility for the industry to lead the process of developing and testing gear solutions is investigated as a potential way to help with the growing demand for a larger number of more specialized gears. Having industry-led gear development processes allows for the possibility of testing numerous fishing gears in parallel, as well as establishing a real commercial development and testing phase prior to expensive scientific trials. This parallel development of different gear solutions allows filtering the most promising ones before carrying out a rigorous scientific test. Furthermore, having the industry to collect data on the selective performance of the tested gear can be a cost-effective solution since it avoids the need for scientific staff on board during the development and testing periods (Roman *et al.*, 2011; Uhlmann *et al*., 2011). As collecting gear selectivity data is a labour intensive and time consuming task, the first step was to investigate if the industry could length measure a portion of the catch with enough quality to allow for a correct assessment of the gear selective performance (**Paper 1**). The next step was to scientifically test industry developed gears that went through the entire industry-led gear development process (**Paper 2**; **Paper 4**). As the scientist level of involvement during the gear development and testing phase differed between studies (**Paper 2**; **Paper 3**; **Paper 4**), the new role of scientists and industry in the process is discussed in this thesis. Finally, lessons learnt from these industry-led gear development processes are discussed.

# 3 Fishing gear development

Fishing gear development is defined in this study as the entire process from idea to the development and testing of a new of modified fishing gear. This process is sometimes followed by the direct use of the gear by the industry, or the implementation of the gear in the legislation, if the gear is shown to lead to an improvement and falls outside of what is described in the technical regulations.

The increasing global attention on the ecosystem effects of fisheries led to a shift on the focus of gear development from maximising catch efficiency for the target species to reducing the negative impacts of fishing on the ecosystems (Cochrane and Garcia, 2009). Indeed, research on fishing gear development has been identified as having a key role in achieving environmentally responsible fisheries and therefore supporting fishery management goals (Jennings and Revill, 2007). A good example of the importance of gear development to fisheries management is the fact that most technical regulations are measures to implement more selective gears or define gear characteristics to ensure a certain selectivity (Graham *et al.*, 2007; Enever *et al.*, 2009; Condie *et al.*, 2014; Fitzpatrick *et al*., 2019; Reid *et al*., 2019). However, despite the extensive use of gear regulations, the desired effects of newly introduced gears do not always occur due to simple and, in many cases, legal modifications made to the new gears that reduce or negate their intended selectivity (e.g. Krag *et al.*, 2016). The perceived or actual reduction in wanted catches, resulting in short-term economic losses, is the main motivation for fishermen to negate the selectivity of a newly implemented gear (Suuronen and Sardà, 2007a; Suuronen *et al.*, 2007; Krag *et al.*, 2016). This negation of selectivity can occur when the technical solutions that are available for use within an entire fishery and management area are perceived by the industry as inadequate (Suuronen *et al.*, 2007). Regardless of the issue at hand, when developing new fishing gears it is important to find the balance between solving the issue and maintaining the economic viability of the fishery (e.g. avoid or minimise loss of commercial catch). However, with the introduction of catch-based management systems, achieving the improvement of overall fisheries selectivity becomes more and more challenging due to the increased level of complexity in objectives (Fauconnet and Rochet, 2016).

This is particularly the case for demersal trawl fisheries, where discard rates are still high (Cashion *et al*., 2018) and multiple negative impacts on the ecosystem are still present (Pilskaln *et al*., 1998; Kaiser *et al*., 2006; Tillin *et al*., 2006; Puig *et al*., 2012), despite this fisheries being the continuous focus of gear development. Moreover, demersal trawl fisheries are among the most important fisheries in European waters in terms of total landings, profit and number of vessels (STECF, 2018). The dominance of demersal trawl fisheries in EU waters and their associated high discards rates is a major factor contributing to the high total discards in EU Atlantic fisheries (Kelleher, 2005; Pérez Roda *et al*., 2019). The North East Atlantic fisheries have the second highest fraction of global discards, accounting for 17% of the 9.1 million tonnes of global discards (Pérez Roda *et al*., 2019). Therefore, most of the examples within this thesis pertain to the demersal trawl fisheries. Specifically, the following sub-section will described the selectivity of demersal trawls, and what can be done to modify the selectivity as part of the gear development process.

## 3.1 Modifying the selectivity of trawls

The size selectivity in a trawl is a consequence of a size selection process that causes the size composition of the catch to differ from that of the population available to the gear during the fishing operation (Wileman *et al*., 1996). Thus, selectivity can be defined as the proportion of individuals encountering the gear which are retained in the catch (MacLennan, 1992). Furthermore, before describing gear modifications, an overview of how bottom trawls capture and select the catch is first needed. The capture process of bottom trawls is a complex sequential process with different levels and types of interactions between the individuals and the different components of the trawl (figure 1). For fish species, individuals first react to the trawl long before they see or come in contact with it. The sound and pressure variations produced by the vessel and the different components of the trawl are detected well before the fish can see the gear (Wardle, 1989; Winger *et al*., 2010). For example, Handegard and Tjøstheim (2005) described how gadoids begin to dive approximately 15 min before the vessel passes them. This behavioural response, as well as most responses to stimuli from the trawl, is most likely an anti-predator response (Fernö and Huse, 2003). Once the fish can see the fishing gear, the main driver for escape behaviour becomes the visual stimuli, e.g. sand-clouds created by the contact of the bridles, doors, and sweeps of the trawl with the seabed (Wardle, 1989). The herding process, i.e. the process where the fish are herded towards the area to be swept by the trawl, starts when the trawl doors are within visual range of fish (Winger *et al*., 2010). During herding, round and flatfish show distinctly different behaviours (Ryer, 2008). As roundfish see the doors approaching, they will start swimming away from it while keeping enough proximity to maintain visual contact with the doors, known as the "fountain manoeuvre" (Wardle, 1993; Winger *et al*., 2010). On the other hand, flatfish swim in burst patterns, contrary to roundfish that have a more continuous swimming behaviour; therefore, flatfish respond to the trawl at shorter distances while staying close to the seabed and swimming for shorter periods of time (Ryer, 2008). Passing the trawl doors, the fish that are in the area between the doors will be guided towards the mouth of the trawl as they swim away from the forward parts of the trawl, e.g. sweeps and bridles (Wardle, 1993, Winger *et al*., 2010). At the trawl mouth, fish will try to swim just in front of it or attempt to flee in different directions (e.g. upwards) and, as they get tired and do not manage to escape, they will enter the trawl (Winger *et al*., 2010). Inside a standard trawl, there is not enough stimuli to encourage fish to escape through the netting (Glass *et al*., 1995); although, as the fish get tired and gradually move towards the aft end of the trawl (referred to as the codend), changes in behaviour might lead to an increased probability to contact the netting (Grimaldo *et al*., 2008; He *et al*., 2008). When in the codend, already exhausted fish will try to swim in front of the accumulated catch and attempt to escape through the meshes directly in front of the catch accumulation (Wileman *et al*., 1996; O'Neill *et al*., 2003). In a standard trawl, most of the size selection of the fish, i.e. trawl selectivity, occurs in the codend (Beverton, 1963; Wileman *et al*., 1996; O'Neill *et al*., 2003). Moreover, the ability of fish to escape is strongly related to their swimming capacity, manoeuvrability, and behavioural responses, which vary with species, length, age and physiological condition of the fish (Winger *et al*., 2010). Therefore, when modifying the selectivity of a trawl, all these factors need to be taken into account.

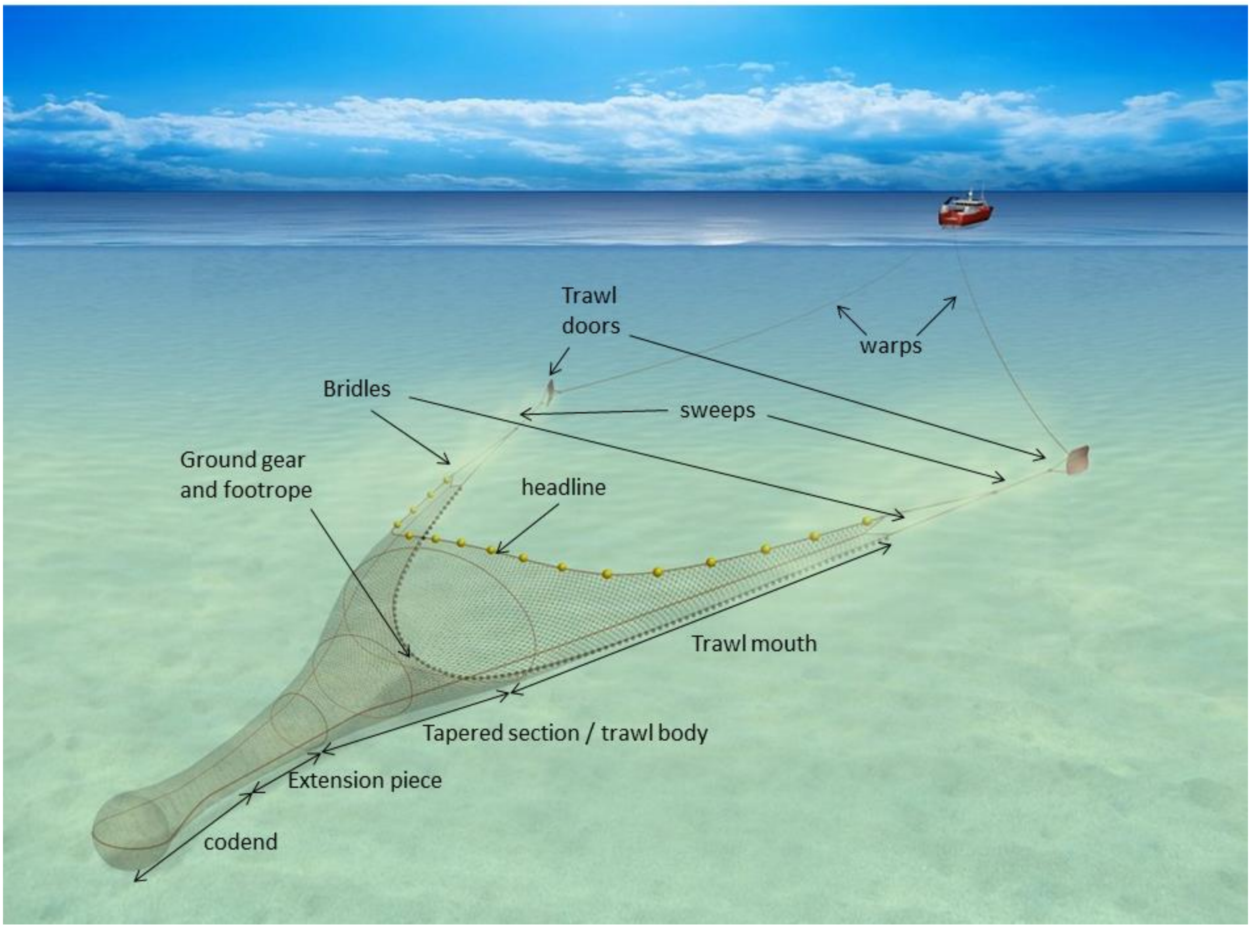


**Figure 1. Different components and sections of a bottom trawl. Figure adapted from www.seafish.org.**

### 3.1.1 Anterior versus posterior gear modifications

A trawl modification, depending on its position from the warps to the codend (figure 1), will affect the selection process differently. Because we can divide the fishing process in two main steps, in front of the trawl (herding) and inside the trawl, two categories for trawl modifications become evident: anterior and posterior gear modifications. Anterior modifications are modifications aimed at preventing individuals from entering the trawl. For example, these modifications can reduce the efficiency of the herding process, e.g. by altering bridles and sweeps of the trawl (He *et al*., 2014; Sistiaga *et al*., 2016); provide counter-herding stimuli to guide fish out of the area to be swept by the trawl, e.g. by adding ropes to the herding area (Ryer, 2008; Melli *et al*., 2018); and provide potential escape routes, e.g. by using topless trawls (trawls where the headline is cut back in relation to the footrope; He *et al*., 2007; Krag *et al*., 2015). Allowing individuals to escape before they enter the trawl is likely to increase their chances of survival, thus reducing the effects of fishing on the ecosystem (Breen, 2004).

Posterior modifications are all modifications to the trawl components aimed at selecting out the unwanted individuals from the catch. These modifications, based on increasing the escape probability of fish that have already entered the netting part of the trawl, have been the main focus of gear development studies (Broadhurst, 2000; Glass, 2000; Suuronen and Sardá, 2007b). Different sections of the trawl have been modified over the years to reduce unwanted catches. For example, escape panels have been placed in the tapered section of the trawl belly (e.g. Briggs, 2010; Santos *et al*., 2016), in the extension piece (e.g. Fraser and Angus, 2019), and in the codend (e.g. Herrmann *et al*., 2014). The most common escape panels are square-mesh panels since their structure ensures they remain open regardless of the longitudinal tension in the netting (Suuronen and Sardá, 2007b). Another common posterior modification are grids, which are usually placed in the extension piece or in the beginning of the codend where it is easier to restrict the grid size while ensuring that a high portion of the catch comes in contact with it (e.g. Grimaldo and Larsen, 2005; He and Balzano, 2007; Larsen *et al*., 2018; **Paper 4**). Moreover, modifying the codend is probably the most common posterior modification used and it can be done by altering several of its parameters, such as: mesh size (e.g. Herrmann *et al.*, 2009; Wienbeck *et al.*, 2011; 2014; **Paper 2**) and shape (e.g. Campos *et al*., 2003; Herrmann *et al.*, 2007), codend circumference (e.g. Reeves *et al.*, 1992; Graham *et al.*, 2009; Herrmann *et al.*, 2015; **Paper 2**), and the thickness and material type of the netting (e.g. Ferro and O'Neill, 1994; Tokaç *et al.*, 2004; **Paper 2**). Some examples of anterior and posterior modifications can be seen in figure 2; for further details on these and other modifications available, see Broadhurst (2000), Glass (2000), and Suuronen and Sardá (2007b).

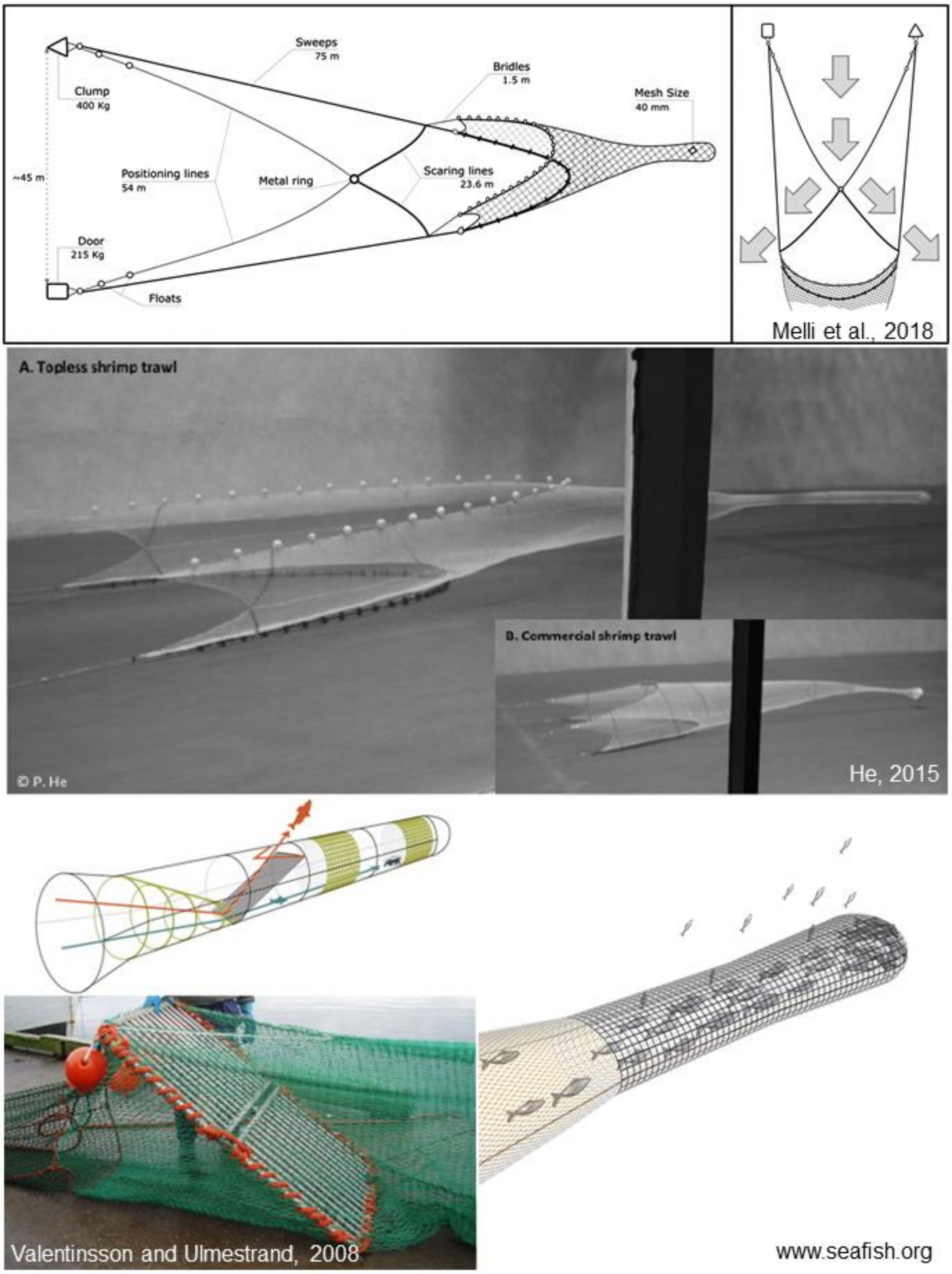


**Figure 2. Examples of anterior and posterior trawl modifications. Top and middle panels show examples of anterior modifications, respectively, FLEXSELECT and a topless trawl. Bottom panels show examples of posterior modifications: Swedish grid (bottom left) and square mesh codend (bottom right).**

### 3.1.2 Mechanical versus behavioural based modifications

The different modifications available for trawls use different mechanisms to achieve their objectives. The different mechanisms can be divided into two major categories: mechanical and behaviour-based mechanisms (Glass, 2000). Mechanical-based modifications use inter and intra species differences in size and morphological characteristics to separate or provide escape opportunities to individuals contacting the fishing gear, while behaviour-based mechanisms use differences in inter and intra species behavioural patterns to achieve the same goals (Glass, 2000; Winger *et al*., 2004). Due to their nature, the performance of behaviour-based modifications tends to be more variable on a haul-by-haul basis when compared to mechanical-based modifications, as individual behavioural responses can vary greatly depending on the species, length, and physical condition (e.g. Winger *et al*., 2010).

Anterior modifications are typically based on behavioural and species-specific characteristics, while posterior modifications use a combination of both mechanisms. A good example of an anterior modification using differences in behavioural responses to facilitate the escapement of fish is topless trawls (Krag *et al*., 2015). In Krag *et al*. (2015), different results were obtained for different species in different sized topless trawls based on how the species reacted to the footrope, either by swimming upwards and over the trawl or simply going over the footrope. Another good example of a behaviour-based modification in the anterior part of a trawl is the lifting of the trawls footrope off the seabed using a number of connecting toggle chains (He, 2007) or simply lifting the fishing line of the ground gear (Krag *et al*., 2010). This modification allows for species that keep in proximity with the seafloor to pass under the net (McKiernan *et al*., 1998; He and Winger, 2010).

Among the different posterior modifications available, there are several examples that are primarily behaviour-based, mechanical-based, or use a combination of both mechanisms. Separator trawls, trawls with a horizontal panel inserted inside the trawl after the footrope, and horizontally separated codends are good examples of behaviour-based modifications (e.g. Krag *et al*., 2009; Fryer *et al*., 2017). Both use the same principle to separate the catch: differences in species' vertical distributions within the trawl, which are mainly associated with differences in behaviour, either in the front section of the trawl (separator trawl) or in the aft section of the trawl (divided codend). Grids and sieve panels, i.e. nets consisting of large mesh placed inside the trawl at an angle to separate the catch on a size basis, are good examples of mechanical-based modifications (e.g. Polet *et al*., 2004; Grimaldo *et al*., 2005; Larsen *et al*., 2018; Santos *et al*., 2018a; **Paper 4**) and are based on similar principles: the physical ability of the individuals to pass through the openings. Although mainly mechanical-based, the sorting performance of these modifications can vary from species to species due to differences in behaviour inside the trawl (reviewed in Broadhurst, 2000). The efficiency of escape panels, on the other hand, depends on both mechanical and behavioural mechanisms (Herrmann *et al*., 2014; Santos *et al*., 2016). Although the size of the fish that are able to pass through the panel depends on the size and opening angle of the meshes of the panel (mechanical), the placement of the panel inside the trawl and the construction of the panel section will also affect the contact probability (behavioural) (e.g. Hermann *et al*., 2014; Santos *et al*., 2016; Krag *et al*., 2016).

### 3.1.3 Species versus size selectivity

Regardless of where in the trawl the modifications are placed, or if they use mechanical or behavioural-based mechanisms, the aim of the modifications can be to reduce the catch of unwanted species (bycatch) and/or the catch of undersized individuals. When bycatch species are larger than the target species, e.g. bycatch of fish in crustacean fisheries, species selectivity can be achieved by mechanical means using grids such as the Turtle Excluder Device (TED; Jenkins, 2012) and the Nordmøre grid (Broadhurst, 2000; Grimaldo, 2006; Valentinsson and Ulmestrand, 2008). However, in cases where the unwanted species has a size and morphology similar to the target species (e.g. cod in demersal mixed-species fisheries in the North Sea), it is difficult to achieve species selectivity via mechanical mechanisms such as grids and codend configurations (Sistiaga *et al*., 2011; Krag *et al*., 2015). Nevertheless, if the behavioural patterns of the species during the fishing process are different enough, these species can be separated using behavioural mechanisms (e.g. Hannah *et al*., 2005; Krag *et al*., 2015; Melli *et al*, 2018; Fraser and Angus, 2019).

Size selection is most commonly used to increase the probability of undersized individuals to escape. Since the codend is where most size selectivity occurs in a trawl (Beverton, 1963; Wileman *et al*., 1996; O'Neill *et al*., 2003), several studies have focused on understanding the selectivity in the codends (e.g. Reeves *et al.*, 1992, Tokaç *et al.*, 2004, Herrmann *et al.*, 2009; Wienbeck *et al.*, 2014). Grids and escape panels are also devices commonly used for size selectivity (e.g. Broadhurst, 2000; **Paper 4**). Moreover, as the complexity of the catch composition increases (e.g. mixed-species fisheries), the need to combine species and size-selective devices in a fishing gear increases (Suuronen and Sardá, 2007a). In recent years, research on the combined effect of species and size selective devices has increased (e.g. Eigaard and Holst, 2004; He and Balzano, 2012; 2013; Larsen *et al*., 2016; 2018).

## 3.2 How to measure size selectivity

A fishing gear's selectivity can be quantified in absolute terms (e.g. Wileman *et al*., 1996) by collecting length-frequency data of the individuals that entered the trawl and that of what was retained, or in relative terms (e.g. Revill *et al*., 2006; Holst and Revill, 2009), by collecting length-frequency data of the individuals retained in both gears (usually modified versus baseline). Estimating the absolute selectivity of a gear allows for the comparison of that gear with any other gear for which the absolute selectivity has been estimated. In contrast, the relative selectivity allows only for the comparison of the gears tested. Moreover, the absolute selectivity is usually described using two parameters: the length for which on average 50% of the individuals are retained in the gear (L50), and the selection range (SR) which is the difference in the length between the 25% and 75% retention probabilities (figure 3).

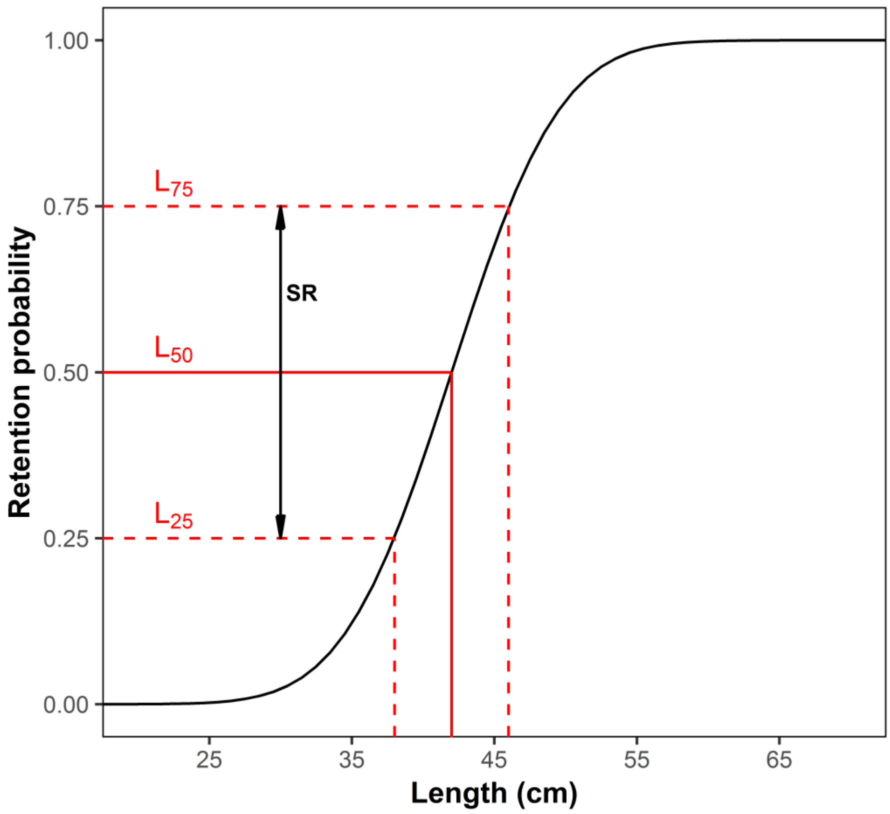


**Figure 3. Example of a typical curve for absolute selectivity of a trawl gear. L50 and SR (L75-L25) are depicted.**

The absolute selectivity of a given codend or trawl gear design can be estimated based on different methods (Wileman *et al*., 1996). The covered codend method uses a cover with small mesh size attached around the codend. This cover retains the individuals that escaped through the codend. However, the cover should be designed and attached to the gear in such way that does not affect the ability of individuals to escape from the codend (Wileman *et al*., 1996; Madsen and Holst, 2002). Moreover, the mesh size of the cover should be of a size that does not allow the escapement of any individuals that could escape from the codend (O'Neill and Kynoch, 1996). In cases where there can be two or more escaping opportunities for individuals that entered the trawl (e.g. grids or escape panels), more covers can be placed along the trawl to capture all escapees (e.g. Larsen *et al*., 2016; Santos *et al*., 2016; Stepputtis *et al*., 2016; Brčić *et al*., 2017a).

The remaining methods for estimation of absolute selectivity can be grouped in a category referred to as paired-gear methods (Wileman *et al*., 1996). These include methods using two trawls towed in parallel, either by the same vessel (twin trawl) or by two vessels each one towing one trawl (parallel haul); one trawl with a vertically divided codend (trouser trawl); or two trawls towed in alternated hauls (Wileman *et al*., 1996). For all methods, one of the codends tested has small meshes, similar to the cover in the covered codend method and referred to as "control", to allow for the estimation of the population fished upon. Out of all the methods available for estimating absolute selectivity, the cover codend method is the preferred method, whenever possible. This method allows to directly quantifying the amount of fish that escape the trawl, while the other methods only provide estimates of the escapement from the trawl (Herrmann *et al*., 2007; Sistiaga *et al*., 2009). Moreover, the amount of data needed to provide the same level of uncertainty in the selectivity estimate is around 10 times higher for the paired-gear methods than for the covered codend method (Herrmann *et al*., 2016). Nevertheless, as stated by Wileman *et al*. (1996), gear selectivity trials should be conducted on-board commercial vessel whenever possible, thus the method used to estimate the test gear selectivity will depend on the conditions available. For example, a smaller vessel might not be able to tow or handle a large cover, thus, a paired-gear method needs to be used.

The relative selectivity can be estimated by comparing the catch of two gears using a method referred to as catch comparison (Revill *et al*., 2006; Holst and Revill, 2009). This method can be interpreted as a variation of the paired-gear methods for absolute selectivity estimates, although here no control gear is used. Moreover, the amount of data required for a given uncertainty level associated to the relative selectivity estimates is similar to that found by Herrmann *et al*. (2016) for paired-gear methods for absolute selectivity (**Paper 1**). Comparing the catch length distributions of two gears allows understanding the effects of a gear modification on the selectivity of a standard gear (e.g. Sistiaga *et al*., 2015; **Paper 2**; **Paper 4**); for a direct comparison of the effects of one or more gear modifications (e.g. Krag *et al*., 2008, 2015; **Paper 2**); and to compared the overall selectivity of two gears regardless of the modifications (e.g. Revill *et al*., 2006; Holst and Revill, 2009). An advantage of the catch comparison method is that it allows for the testing of the gears to be conducted under full commercial conditions, including commercial towing time and catch sizes, which often is difficult in experiments using covered or control codends (Wileman *et al*., 1996). Moreover, it can be applied to several types of fishing gears, i.e., both passive (e.g. Brčić *et al*., 2017b; Herrmann *et al*., 2017; Savina *et al*., 2017) and active (e.g. Krag *et al*., 2015; Sistiaga *et al*., 2015; **Paper 2**; **Paper 4**).

## 3.3 From traditional to industry-led fishing gear development

### 3.3.1 The traditional process for gear development

Traditionally, the process for the development of a fishing gear starts with the identification by managers or scientists of an issue with a given fishery, area, or species (Eliasen *et al*., 2019), e.g., the need to protect endangered marine turtles (Seidel and McVea, 1982; Crouse *et al*., 1987) or to ensure the recovering of a stock, e.g. North Atlantic cod (*Gadus morhua*) stocks (Cook *et al*., 1997; Myers *et al*., 1997). For example, following the identification of these two problems, a series of fishing gear modifications were developed and tested to alleviate the issues such as TEDs (e.g. Seidel and McVea, 1982; Robins-Troeger, 1994; Sala *et al*., 2011; Jenkins, 2012) and modifications aiming at reducing cod catches in mixed trawl fisheries (e.g. Madsen *et al*., 1999; Beutel *et al*., 2008; Krag *et al*., 2010; Fraser and Angus, 2019). In these tests, as in the majority of scientific tests of fishing gears, one single aspect of the gear was altered aiming at solving the identified issue, to be able to quantify the effect of the modification developed (Eliasen *et al*., 2019). If funding allows, preliminary assessment of the modification can be performed in a flume tank (Winger *et al*., 2006; Madsen *et al*., 2010), allowing for additional adjustments to the design prior to scientific tests at sea. The scientific testing of the gear modification is usually performed on board chartered commercial vessels (e.g. Krag *et al*., 2016; Fraser and Angus, 2019, **Paper 2**; **Paper 4**) or research vessels (e.g. Melli *et al*., 2018, Santos *et al*., 2018b). The results of the tests are then published in reports or in scientific literature. Overall, the entire process from idea and applying for funding, to developing and testing of the new or modified gear, is time consuming and economically costly (Eliasen *et al*., 2019). Even if the new or modified gear is deemed successful, several years can pass until the gear is implemented in the technical regulations (Eliasen *et al*., 2019). Figure 4 depicts the traditional process from the development of a gear to the implementation process of such gear in the EU technical regulations.

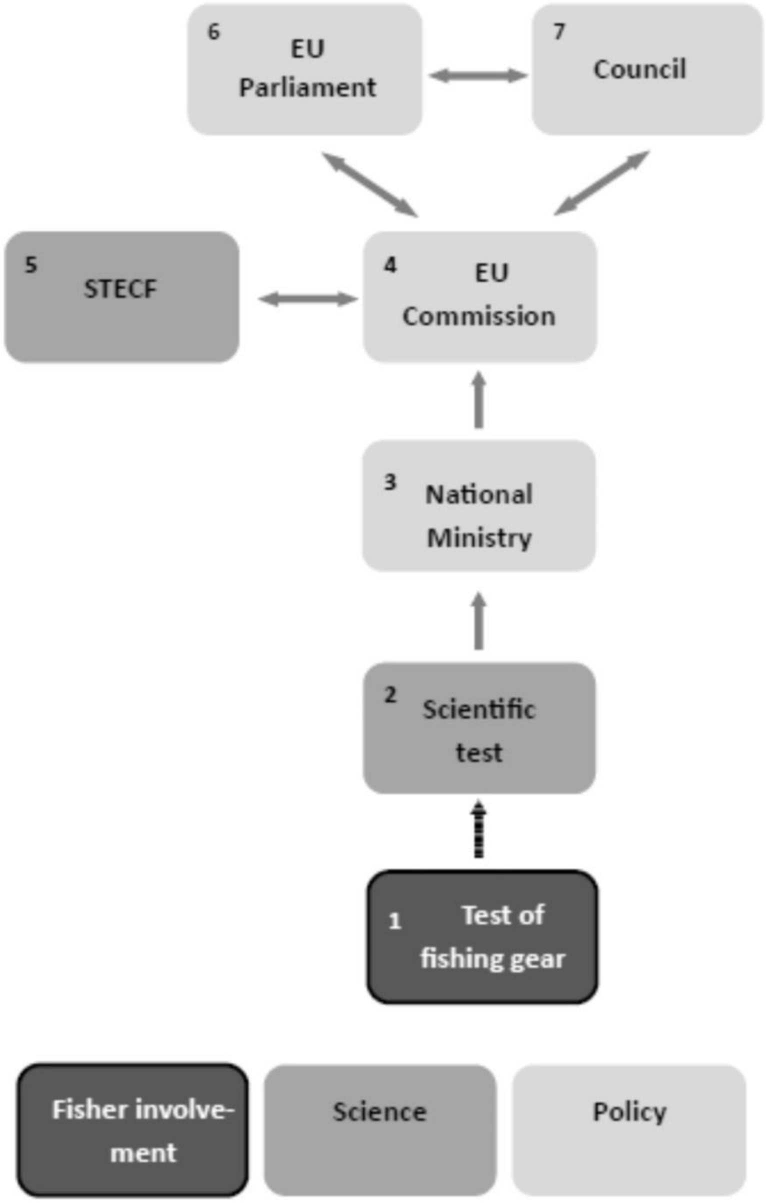


**Figure 4. Flow diagram describing the main elements used for the evaluation and implementation of new fishing gears under the current technical regulation. Type of actor marked by colour. Figure from Eliasen *et al*. (2019).**

### 3.3.2 Greater stakeholder involvement

Greater stakeholder involvement has been continuously and increasingly mentioned as an important step to improve the effectiveness of fisheries management (e.g. Smith *et al*., 1999; Armstrong *et al*., 2008; Berghöfer *et al*., 2008; Mikalsen and Jentoft, 2008; Mackinson *et al*., 2011; Condie *et al*., 2014; Salomon *et al*., 2014; Karp *et al*., 2019). One way to increase stakeholder involvement in gear development is through collaborative initiatives between scientists and fishing industry (e.g. Kaplan and McCay, 2004; Armstrong *et al*., 2008). Collaborative research, defined as a scientific activity involving two or more partners with mutual gain (CRCMWG, 2015), has previously been used in fisheries management with different degrees of success (e.g. Armstrong *et al*., 2008; ICES, 2008; Catchpole and Gray, 2010; CRCMWG, 2015). These projects increase fishermen's sense of ownership over their fisheries and the trust between the different stakeholders, while also taking advantage of fishermen's experience-based knowledge (Kaplan and McCay, 2004; Feeney *et al*, 2010; Lordan *et al*., 2011; Armstrong *et al*., 2013; Kraan *et al*., 2013). Other important advantages of collaborative initiatives between scientists and industry have been identified by several authors and listed by Pita *et al*. (2010). These advantages include: facilitating common understanding, resolving/avoiding conflicts, increasing stakeholders' responsibility and accountability, enhancing the legitimacy and acceptance of management policies and decisions, and contributing to more effective enforcement of rules and regulations by increasing the likelihood of compliance (Pita *et al*., 2010). However, if the expectations for project outcomes are not fully aligned between the different participants, difficulties when considering mid and long-term initiatives might arise (Johnson and van Densen, 2007; Catchpole and Revill, 2008; Hoare *et al*., 2011; Lordan *et al*., 2011). Fishermen, for which short-term expectations are most common and important, might lose interest in the project, especially when the results do not align with those expectations or take too long to become available to them (Hoare *et al*., 2011; Kraan *et al*., 2013). This highlights the importance of good communication between fishermen and scientists (Lordan *et al*., 2011; Mangi *et al*., 2016). When fishermen understand and agree with the importance of a project's goals, they might continue the work even after the project has ended (Mangi *et al*., 2016).

Collaborative research initiatives between the fishing industry and science have been developed to supplement many aspects of fisheries management, from the collection of data for stock assessment purposes (e.g. Kraan *et al*., 2013; Mangi *et al*., 2016), monitoring of unwanted catches and by catches (e.g. Pita *et al*., 2010; Mackinson *et al*., 2011), to the development of technical measures (e.g. Catchpole and Gray, 2010; Armstrong *et al*., 2013). Among those, gear selectivity initiatives, due to their nature, are where experience-based knowledge from the fishermen can be most useful and fully integrated throughout the entire process (McCay *et al*., 2006; Johnson & van Densen, 2007; Armstrong *et al*., 2013). These initiatives also provide fishermen with the possibility to define solutions for specific problems within specific fisheries that might not be apparent for scientists or managers. Furthermore, the involvement of industry in the gear development process allows them to better understand the scientific perspective of the process. This is something which can ultimately facilitate the acceptance of gears developed by scientists since fishermen may sometimes consider the work from scientists to be too theoretical and out of touch with the reality of commercial fisheries (Suuronen and Sardà, 2007a). Nonetheless, industry involvement in the gear development process does not ensure that the effects of modifications implemented in the legislation are not negated (e.g. Krag *et al*., 2016). A further step for these gear selectivity initiatives is, rather than just involving the industry, having them lead the gear development and testing processes (ICES, 2018). Industry-led fishing gear development initiatives are defined here as collaborative initiatives where the fishing industry has the leading role in identification of ideas, development and initial testing of a new fishing gear (figure 5).

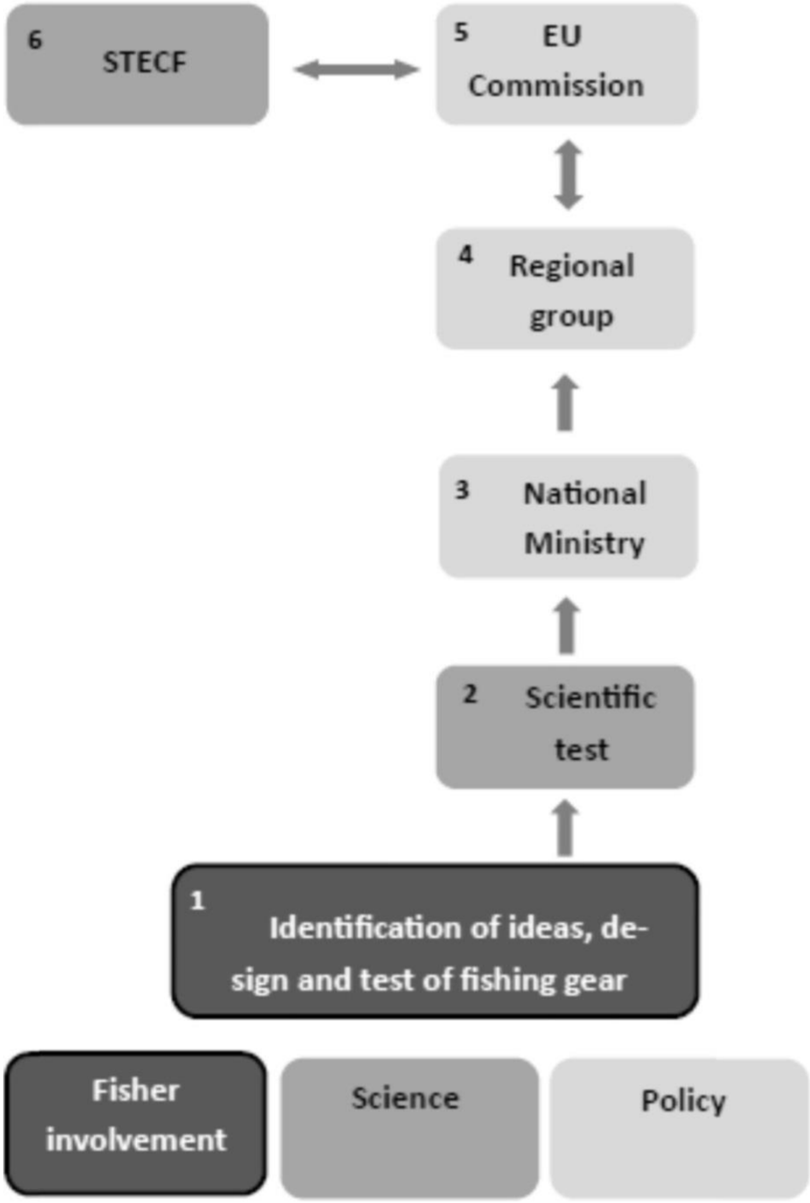


**Figure 5. Flow diagram describing the possible main elements in the process of identifying, developing, testing, documenting and evaluation of new selective gear leading to political implementation in multi-annual management plans under the proposed technical regulation. Type of actor marked by colour. Figure from Eliasen *et al*. (2019).**

# 4 Industry-led gear development

As previously describe in section 1.2, the LO creates a need for more specific fishing gear solutions to be available to the industry. To be able to sufficiently address these issues within a relative short period, the current gear development process would require an increase in man hours and money since the number of solutions needing to be tested would be greater. Therefore, having the industry identifying the specific issues they will have in their fisheries under the LO, and developing and testing gear solutions for those issues, seems to be an intuitive solution. Moreover, as suggested by O'Neill *et al*. (2019), the industry should be encouraged to participate in a meaningful way and in a regulatory environment that allows them to develop and use new gears. Therefore, the possibility of the industry taking on a greater role in gear development and testing was investigated during this work. This gear development process was divided into two main phases: i) industry-led gear development; ii) scientific trials. Figure 6 depicts the different processes within the industry-led gear development and scientific testing phases; these are described in detail in sections 4.1.1 and 4.1.2. Also described in the following section, although not investigated during this PhD thesis, is the implementation of the gears in management (section 4.1.3).

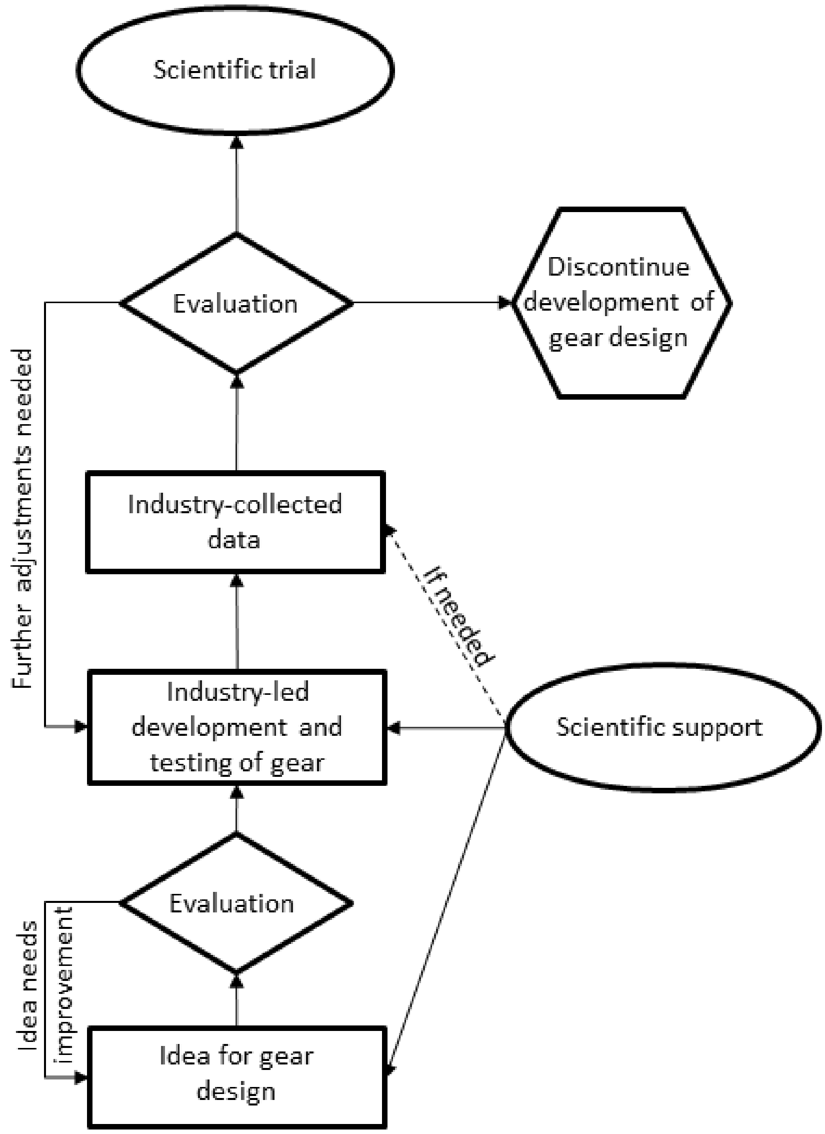


**Figure 6. Flowchart depicting the main steps in a single industry-led gear development process, from idea to scientific testing.**

## 4.1 The different stages of gear development

### 4.1.1 Gear development stage

The industry-led gear development process described here pertains to the first step in figure 5, and is shown in greater detail in figure 6. This process starts with industry identifying an issue within a fishery and a specific solution being proposed, either by the industry or in collaboration with scientists. For example, proposing a new codend design because the selectivity of the current legislated gears is not suitable for the population size structure of the target species (**Paper 2**). Moreover, the proposed gears aim at addressing issues that the currently legislated gears within a fishery cannot solve. Therefore, these gears should be tested using a catch comparison approach since it allows for the direct comparison of the selective performance of the new gear in relation to the legislated gear. During this testing phase, fishermen decide when, where and how to fish during the trials, as well as if further adjustments to the gear are necessary. Scientists are involved throughout this entire process to provide the necessary support or advice (**Paper 2**; **Paper 3**; **Paper 4**). The combination of industry-led testing, adjusting and initial data collection and scientific analysis and feedback to the industry creates an important iterative gear development process (figure 6).

For each iteration, the gear is evaluated by the industry in terms of its overall performance; this evaluation process can also be supported by scientists if data from such tests are provided (**Paper 1**). These data are important for the industry-led gear development process, since they are used to evaluate the selectivity of the new gear and to decide if a gear goes through to scientific testing, if it needs further development, or if the development of this specific design should be discontinued. Therefore, the industry-collected data needs to allow for a correct assessment of the new gear's selective performance. As the selective performance of most gear modifications is expected to have a size-dependent effect, length-based data should be provided by the industry. However, an understanding of what can be obtained in terms of industry-collected data is important for the success of this type of initiative. **Paper 1** is a good example of a study where the minimum sampling effort required for a correct preliminary assessment of a gear's selective performance using length dependent data was determined *a priori*. It was shown that relatively small sample sizes provide enough information to correctly assess the performance of the gears using the catch comparison approach (**Paper 1**). The relatively low sampling effort required indicates that industry can collect quality data on the selective performance of a new gear without affecting their main activity (**Paper 1**). Moreover, scientists also need to provide the necessary support to the industry during the gear development and testing (Catchpole and Gray, 2010; **Paper 2**). As demonstrated in **Paper 2**, the involvement of scientists at the early stages of an industry-led gear development process is important to avoid underdeveloped or overcomplicated gears being tested in the scientific trials. Nonetheless, scientists involvement should not only be at the early stages but also continuously throughout the gear development process. Finally, having the industry lead the gear development stage allows for a large number of potential gear solutions to be tested in parallel on several different vessels operating in different areas. From those, the gears that are considered the most promising for a given fishery will go through to the next stage, the scientific testing (figure 6).

### 4.1.2 Scientific trials

The scientific testing stage, led by scientists, allows for the scientific documentation of the selective performance of new gears that have been developed and tested by the industry. This step is essential for the potential implementation of new gears in legislation, since it provides the necessary documentation required by managers and scientists (Eliasen *et al*., 2019). Trials led solely by the industry may not always be fully substantiated in a scientific context (Reid *et al*., 2019), despite trial and data collection protocols being designed together with scientists. Indeed, the gear development is industry-led but the final documentation of the gears selective performance is science-led (**Paper 2**; **Paper 4**). Additionally, the scientific trials should be undertaken on board fishing vessels to facilitate their testing under conditions which are representative of commercial fishing.

These scientific trials can be designed in many ways (as described in section 3.2). However, trial designs following the catch comparison method are preferred during this stage since they provide the selectivity of the new gear relative to the selectivity of a gear that is already implemented. Such trial designs should ensure that the scientific documentation is sufficient to facilitate their implementation in management (EC, 2016). However, this is only pertinent for those gears that fall outside of the technical specifications of the legal gears, since gears with modifications that fall inside of what is described in the technical regulations can be directly adopted by the industry.

### 4.1.3 Gear implementation process

Following the scientific trial, and assuming that the objectives of the trial are achieved, the results are reported to the national fisheries managers to initiate the implementation process (figure 5). This stage was not investigated during this study, but it is essential for the entire gear development process, from idea to implementation. As stated in the proposed new technical regulations (see section 1.3.2), national managers can request for the European Commission to implement a new gear. This can be done through annual joint recommendations from regional groups or on an *ad doc* basis, if deemed necessary (Eliasen *et al*., 2019). Since the European Commission can now approve joint recommendations from the regional groups without consulting the European Parliament and Council, the time needed for the implementation of a new gear can be greatly reduced (Eliasen *et al*., 2019). Moreover, there seems to be no limit on the number of new gears that can be presented in annual joint recommendations (EC, 2016; Eliasen *et al*., 2019). Therefore, the number of new gears going through this framework can be far greater than the current one. Nevertheless, the European Commission can request scientific advice on the new gear to the Scientific, Technical and Economic Committee for Fisheries (STECF), which can request further documentation to the national managers and scientists. This process can have several iterations, thus, increasing the time needed for the implementation of a gear. If the STECF advice on the new gear is positive, the gear is implemented in the technical regulation for that region.

## 4.2 Fishermen can successfully contribute to gear development…

### 4.2.1 The industry can collect length based data

The industry-led gear development phase presented here requires industry to collect data to correctly describe the selective performance of the new gears. **Paper 1**, as previously mentioned, demonstrated that it is theoretically possible for the industry to collect length-based data to describe the performance of a new gear. Based on the results of **Paper 1**, fishermen were asked to length measure a part of the catch; approximately 40-50 individuals per species and gear from several hauls, but no less than 500 individuals in total per species. The data collect by the fishermen, 550 individuals collected over 7 hauls, were analysed using the catch comparison method. The same codends were tested during the scientific trial (**Paper 2**) where the entire catch was measured (5856 cod collected over 6 hauls). The estimated average catch comparison curves for both datasets were very similar, especially for the lengths where the data are strongest (figure 7). This shows that it is possible for the industry to collected length-based data to indicate the selective performance of the new gear. Furthermore, this also validates the theoretical results obtained in **Paper 1**.

Depending on the target species, it might not be possible for the industry to length-measure the catch on board. For example, shrimps can be harder and more time consuming to measure or may need specific tools to be properly measured (e.g. callipers). In those cases, samples can be collected by the industry and then processed on land by scientists (e.g. **Paper 4**). Moreover, as the objective of the preliminary data collected by the industry is to allow for a correct assessment of the modified gear, there might not be the need to take length measurements at this stage of the process. If the objective of the modification is to reduce bycatch, regardless of length, a gear that shows large differences in total catch weights of the different species when compared to the standard one should also be considered for scientific testing (Nilsson *et al*., 2018; ICES, 2018). The data collection protocol for each industry-led gear development initiative should be tailored not only to the data requirements, but also to the aims of the gear solutions and the conditions of each specific fishery and vessel. Such flexibility is important for the success of these initiatives, since it avoids excessive and unnecessary workloads for fishermen; something which could reduce the motivation from industry to participate in such initiatives.

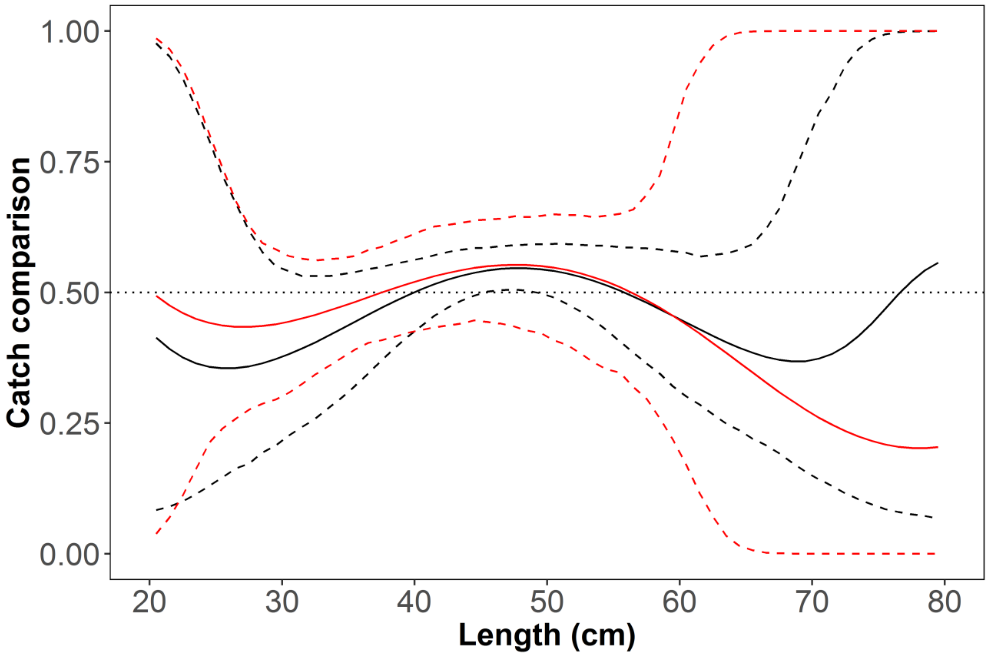


**Figure 7. Catch comparison curves (solid lines) and respective 95% confidence intervals (dashed lines) resulting from industry-collected (red lines) and scientist-collected data (black lines) on the selectivity of the same fishing gears.**

### 4.2.2 Gears developed by the industry have higher chance of uptake

Not only having the industry identifying the specific issues in the fisheries and proposing solutions but also developing and testing the gears makes gear development much more relevant for management. The gears that go through this process are developed and tested not only to improve the selective performance but in other aspects such as handling of the gear during fishing process or when retrieving the catch (**Paper 2**; **Paper 4**). Even if a gear is proven to improve the selectivity of a fishery, a complex or difficult handling will lead to a lower uptake from the industry (Valdemarsen and Suuronen, 2003). Thus, gears developed by the industry have a higher chance of uptake by the fishermen, since such gears have been tested under true commercial conditions and their handling approved by the fishermen testing it.

### 4.2.3 Parallel development and testing of different gear solutions

One of the most important advantages of the industry-led gear development is the possibility for the multiple processes of development and testing of different gear solutions. This advantage is of particular importance when considering that an effectively enforcement LO will greatly increase the demand for gear solutions available to the industry, something which the current gear development framework cannot supply in time. The simultaneous development and testing of several potential gear solutions greatly increases the capacity for a fisheries management system to find the most suitable gear solutions for a given issue with a fishery. This is particularly true when considering that the traditional gear development process for each country or area can only scientifically test a few gears every year, which may or may not have the expected results. By having several industry-led gear development initiatives running in parallel the most promising gear solutions, after being properly developed and tested by the industry, can be scientifically tested with higher probability of success. This is due to the possibility of filtering the best ideas for gear solutions from a far greater number than it was possible before. Moreover, these new gears can be proposed to the European Commission, through the annual joint recommendations from regional groups, to be implemented in the fishery legislation when deemed necessary by national fishery managers. Thus, the industry-led gear development phase described here not only increases the capacity for a country to produce a higher number of potential gear solutions but also uses the flexibility that is being added to the European fisheries management system to facilitate the time needed and the implementation process of these new gears.

## 4.3 … but a continuous collaboration between scientists and industry is necessary

Some potential issues with an industry-led gear development phase were also identified throughout this study. By having the industry lead the gear development process scientists have less control of the final gear, despite being involved in the entire process as support providers. The industry, e.g. fishermen, has the final say on what they are willing to test and what modifications should be done to the gear. This can be an advantage since it can avoid unpractical modifications made to the gear, but it can also reduce the selective potential of the developed gear.

### 4.3.1 The industry can produce over complicated gears

As shown in **Paper 2**, the industry can produce gears with modifications that have antagonist effects or that are overly complicated. Gears that are too complex may be more difficult to implement in the legislation both at the national but also European level. An early and continuous collaboration between scientists and industry during the process of gear development can help solve this issue (**Paper 2**). If a gear is too complex, its technical description in the national legislation can be difficult to set, something which can delay the implementation of the gear in the legislation. Additionally, the information needed to fully describe the selective performance of a complex gear can be extensive. Therefore, during the gear's implementation process in the European legislation, the European Commission, through STECF, may request further information which ultimately would delay the process. These delays, both at a national and European level, are something that can hinder the success of an industry-led gear development process.

### 4.3.2 Potential need for further research

In some cases, a greater understanding around the proposed modification may be needed that cannot be obtained solely from gear selectivity trials or that require skills or facilities that the industry might not have. This can be in the form of getting a better understanding around certain parameters potentially affected by the modification proposed such as structural issues in the gear or hydrodynamic issues. In these cases, the use of facilities such as flume tanks (e.g. Winger *et al*., 2006) or wind tunnels (e.g. **Paper 3**) may be necessary to further improve the proposed gear solution. For example, in **Paper 3**, a pre-development test was needed since it was observed that the grid suggested by the industry could have poor hydrodynamic properties. Due to the small size of the target species, brown shrimp (*Crangon crangon*), and the desire to reduce the capture of small individuals, the industry wanted to test a size sorting grid with a bar spacing of 6 mm. The idea was that such small bar spacing could entail hydrodynamic issues that may hamper the sorting capacities of the grid. Therefore, to optimise the hydrodynamic performance and possibly the selective performance of the grid, grid angle, porosity, and bar shape were tested in a wind tunnel (**Paper 3**). This pre-development test made it possible to define the optimal grid angle (30°), porosity (over 60%) and bar shape (drop or rectangular shape) to maximize water flow. Those findings were used in the industry-led development and subsequent scientific-led phases (**Paper 4**).

**Figure 8. The T90 codend proposed by the industry for the Baltic cod demersal trawl fishery. The codend has 92 meshes in circumference (left panel), a mesh size of 115 mm (top right panel) and lastridge ropes (bottom right panel).**

### 4.3.3 Iterative process between industry and scientists

An industry-led gear development phase also allows for a more extensive and thorough development and testing of potential gear solutions. This is done through an iterative process between industry (leading the process) and scientists (providing support). This iterative process can be more or less extensive depending on the gear proposed for development and testing. For example, the codend described and tested in **Paper 2** (figure 8) was based on a codend tested by Swedish fishermen that had shown positive results (Sundelöf and Ovegård, 2018), thus the iterative process was relatively short. On the other hand, the size sorting grid for brown shrimp developed during this study (**Paper 4**) was a good example of a longer iterative gear development process. During the development of the grid, several iterations were performed where adjustments of the grid were tested under commercial conditions (figure 9). For each one of the iterations, underwater videos were recorded, and catch samples collected to better understand how the grid was performing both during the fishing process and in terms of selectivity. Throughout the different iterations, both fishermen and scientists identified issues with the grid and suggested solutions to improve the grid's selective performance (figure 9). Following the first test of the grid, the skipper showed a lack of confidence in the grid as a solution. With the continued development of the grid, the skipper's confidence in the grid increased as the issues were resolved. Moreover, the final design of the grid was tested in a scientific trial and shown to achieve its objective of reducing the capture of small shrimps (**Paper 4**). This iterative process can potentially maximize the outputs of gear development initiatives since the gears have several cycles to improve both selective performance and handling during the fishing process. Thus, it minimizes the chances for good ideas that did not performed well in the first cycle of testing to be dropped. Moreover, this iterative process ensures that a new gear solution is mature before being scientifically tested and proposed to be implemented in legislation (**Paper 2**).

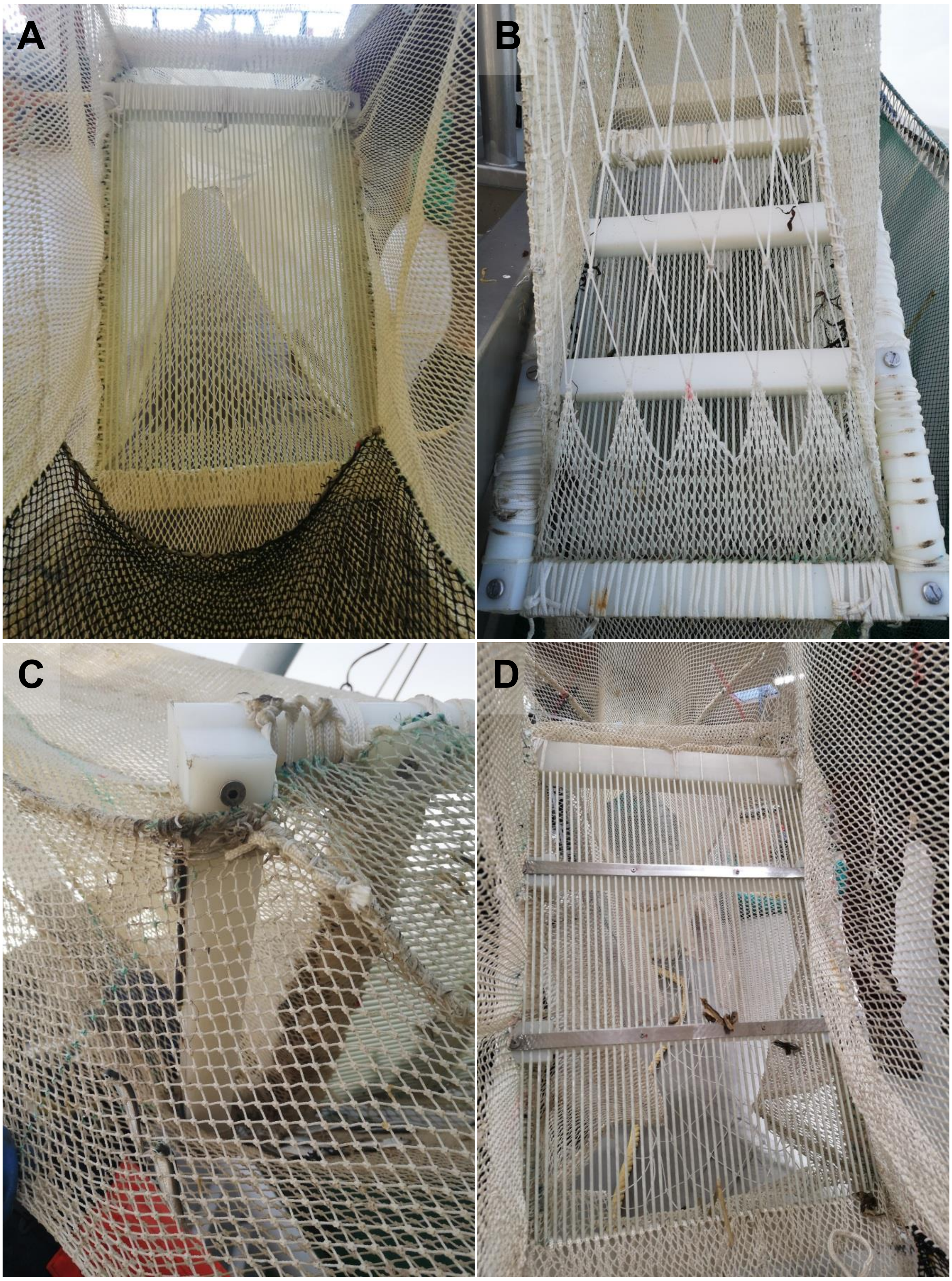


**Figure 9. The four development stages of the sorting grid developed for the brown shrimp beam trawl fishery. From the original grid design proposed by the industry (A) to the final grid design (D) that was tested in a scientific trial. From stage A to B, the mesh size of the escape panel was increase and the thick horizontal bars added to support the grid's bars. From stage B to C, the member of the grid frame was detached from the top panel of the extension piece to increase the area of the entry to the codend. From stage C to D, the horizontal support bars were reduce in size and thickness and the frame section of the grid's opening for the codend cut out.**

# 5 Final remarks and future work

The industry-led gear development process presented here was successfully developed and tested as a potential way to produce the necessary toolbox of gear solutions for the issues arising under the EU landing obligation (**Paper 1**; **Paper 2**; **Paper 4**). This process allows for numerous gear solutions to be developed and tested in parallel (e.g. **Paper 2**; **Paper 4**), which provides a greater number of solutions available to the industry in a shorter time span than what is possible with the traditional gear development process. Therefore, the industry-led gear development process takes full advantage of the flexibility in gear development to be added as part of the proposed new EU technical measures framework. Moreover, having the industry lead this process provides sufficient time to fully develop and commercially test the ideas before testing them in costly scientific trial, thus allowing for filtering the best ideas. It also allows for a faster identification of the different and most pertinent issues arising in the fisheries. However, an early and continuous involvement and support by scientists during industry-led gear development process was found to be crucial for reaching the full potential of this process (**Paper 2**; **Paper 3**).

An important step in the process described here, is the ability for the industry to provide gear selectivity data with sufficient quality to allow for a correct preliminary assessment of the gear's selective performance. This step was theoretically proven to be possible in **Paper 1** and experimentally demonstrated during this thesis using the findings from **Paper 2**. The ability for the industry to collect even labour intensive data, individual length-based data, ensures that more complex gear designs that require length-based data to be properly evaluated can be tested by the industry. However, simpler designs with straightforward objectives (e.g. sorting grid to reduce the overall catch rate of bycatch species) might not need these more labour intensive data to be collected for a preliminary analysis. For those cases, it should be investigated what are the minimum data requirements (e.g. number of hauls) to allow for a correct preliminary assessment of a gear's selective performance. Furthermore, the potential of using REM with Closed-Circuit Television (CCTV) should be investigated as a way to further facilitate the industry-led gear development process. Previous studies have shown that this method allows for the detection of individual fishes on video (e.g. Stanley *et al.*, 2011; van Helmond *et al.*, 2014), although less accurately in the case of mixed bottom trawl fisheries (e.g. Kindt-Larsen *et al*., 2011; van Helmond *et al.*, 2014). Therefore, REM could be potentially used as a way to sample the catches during industry-led gear development, thus reducing the time- and workload associated with industry self-sampling.

Understanding what factors affect the hydrodynamics of a grid and how they affect it (**Paper 3**) was important for the development of the size sorting grid described and tested in **Paper 4**. Therefore, further work should be conducted on investigating the hydrodynamics of the different components and possible modifications of fishing gears, particularly trawls, and the factors that affect their hydrodynamic performance. This knowledge could then be used to better adapt the hydrodynamic profile of a gear to meet different objectives. For example, separation of species and sizes based on swimming capacity or increasing the efficiency of different gear modifications by guiding the catch towards it using the water flow inside the gear. Moreover, changing the hydrodynamics of a codend has also been shown to improve the quality of the catch. The use of a sequential codend (Brinkhof *et al*., 2018), where a second codend with smaller meshes attached to the end of the first codend was used. Due to the reduced water flow inside the second codend, the overall quality of the catch was improved (Brinkhof *et al*., 2018), while no changes in the overall catch pattern of the gear was found (Brinkhof *et al*., 2019).

During this study, the initial stages of the industry-led gear development process, from idea to implementation in the legislation, were investigated. Despite an industry-led gear development phase being able to produce a sufficient toolbox of more specific gear solutions, this positive effect can be greatly reduce if the management system is not able to incorporate them in the legislation quickly. Based on the proposed new technical regulations, there seems to be no limit on the number of new gears that can be proposed by the regional groups (EC, 2016; Eliasen *et al*., 2019) but whether those gear proposals can be processed in due time is not clear yet. Therefore, the steps following scientific testing of a gear should be investigated, bottlenecks in the process identified and, if necessary, alternatives processes developed. This would ensure that the full potential of industry-led gear development could be achieved under the new EU Common Fisheries Policy, in particular, under the landing obligation.

Although the industry-led gear development phase aimed at increasing the number of gear solutions available under the EU landing obligation, it has the potential to be applied in any country or management framework. In this study, the main incentive to improve the overall selectivity of the fisheries was the change from a landing- to a catch-based quota system, which is something that has been implemented in several other countries (Condie *et al*., 2014; Borges *et al*., 2016; Karp *et al*., 2019). Moreover, other strong incentives to improve the selectivity of a fishery, such as requirements set out as part of an eco-friendly certification process (**Paper 3**; **Paper 4**), could also benefit from an industry-led gear development phase. Overall, a system that provides an extensive and iterative development phase, that is cost efficient, provides a greater number of potential gear solutions, and that can quickly identify and address arising issues in the fisheries should be considered for any fishery management framework.

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# Paper 1

RESEARCH ARTICLE

# When is enough, enough? Quantifying trade-offs between information quality and sampling effort for fishing gear selectivity data

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## Abstract

There is general pressure throughout the world's fisheries for the industry to have greater involvement not only in the development of fishing gears but also in the testing and documentation of their effect. In the European Union, the Common Fisheries Policy of 2013, together with the proposed reform of the technical measures regulation, highlights the need for greater flexibility in fisheries through increased stakeholder involvement. To achieve this flexibility, there is a need for additional fishing gears available to the fishermen. A way to facilitate this is to have the industry take part in the development and testing of fishing gears, as well as collect data on their performance. However, to have a successful industry-collected data programme, fishermen have to be able to collect data on the length of a portion of the catch. In this study, we determine how many individuals need to be measured to correctly evaluate the relative selective performance of a new gear compared to a standard gear. The evaluation was carried out by analysing catch ratio curves, their associated uncertainties, and the trade-offs between uncertainties and sampling effort. Results show that with relatively small sample sizes (500 to 1000 individuals) it is possible to correctly evaluate the performance of a gear for a given species. By having the industry develop and test their own gears, as well as being involved in the collection of data, the number of potential gear solutions available to address the different issues emerging in the fisheries is increased.

## Introduction

Throughout the world's fisheries there is a general trend for the industry to have a greater involvement, not only in the development of fishing gears, but also in the testing and documentation of their effect [1]. In the European Union, the Common Fisheries Policy (CFP) of 2013, where the catch of all listed species are required to be landed and counted against quota [2], introduces additional pressure on the industry to eliminate or considerably reduce unwanted catch [3]. This unwanted catch can either be species- or size-specific, and its composition can vary depending on the quotas available to each fishing vessel. Thus, the ability of fishermen to adjust the selectivity of their gear to suit the quotas which are available to them

the manuscript. The specific roles of this author are articulated in the 'author contributions' section.

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will be an important factor in determining the revenue and profitability of their fishery. As the combination of gear, fishing practice and quota shares will differ between fisheries and vessels, changes to the selectivity of the gear will need to be applied quickly and at a vessel level. However, to achieve such flexibility a greater number of more specific gear solutions is needed.

Under current EU management, such flexibility is limited, where only a couple of generic gears are legislated for each gear group and area. The current setting is often slow and inflexible, where few fishing gear solutions are tested and new gears take several years to be implemented in legislation. Moreover, the "one gear fits all" type of legislation further reduces the system's flexibility and capacity to adjust to upcoming problems. This lack of flexibility in the legislative framework has been highlighted in the proposed reform of the technical measures regulation as one of the major shortcomings of the current regulation [4].

To achieve the necessary flexibility, there needs to be a framework where a greater number of new gears or modifications to existing gear can be adequately developed, tested, and their selectivity correctly documented. One way to facilitate this flexibility, and to reduce the economic and time outlay associated with the development of fishing gears, is to have the industry not only identify the problems but to develop and test the technical solutions themselves. Increasing the involvement of stakeholders in developing specific conservation measures (e.g. the development of gears) is also something which the proposed reform of the technical measures regulation aims to achieve [4]. The involvement of fishermen in gear selectivity projects, where they are an integral part of the process, has previously been shown to provide valuable experience-based knowledge [5–7]. Furthermore, having the industry identify the problems and test potential solutions helps incorporate them into the process, while also shifting the burden of proof onto the industry. Additionally, the involvement of fishermen in the development of fishing gears allows for a period where promising solutions can be identified and tested in a commercial setting before carrying out a rigorous scientific test. This also allows for the possibility of testing numerous fishing gears in parallel, as well as establishing a real commercial development and testing phase prior to expensive scientific trials. Furthermore, having the industry assist with the collection of data is a cost-effective solution since it avoids the need for scientific staff on board during development periods [8,9].

Despite there being several studies which have shown the validity of industry collected data [8–12], some concerns remain about the possible bias of such data [11–15]. Potential bias can occur if fishermen do not understand why the data are collected, sampling training is lacking and/ or the workload associated with sampling is excessive [9,11,12,16]. While the first two concerns can be addressed through good communication, the issue of excessive sampling effort is not so straightforward. Thus, to have a successful industry-collected data programme, those involved need to be burdened as little as possible. This is because they have another objective, which is to carry out a viable fishery. Therefore, in terms of industry-collected data, a relatively limited sample needs to be able to correctly quantify the performance of a new gear.

In this study, we address the issue of excessive sampling effort and how to minimize this burden by defining how many individuals need to be measured to correctly evaluate the selectivity of a new fishing gear relative to an existing gear. Since the selectivity of a gear is typically different for different sizes of a species, the relative selectivity between the two fishing gears needs to explicitly account for fish size. The relative selectivity can be expressed using the catch comparison method [17] that quantifies the length-dependent relative selectivity between two fishing gears. This method is particularly suitable to industry-collected data as it does not interfere with commercial fishing practices since the two gears are fished in parallel in a twin-rig setting. Previous studies have looked into the issue of how many individuals need to be measured to evaluate the selective performance of a new gear design for covered codend

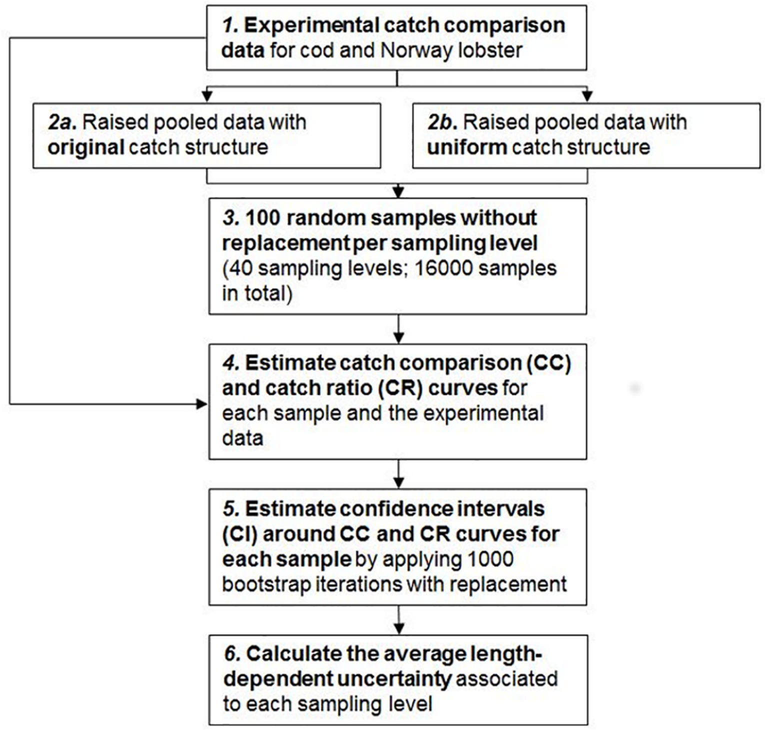


**Fig 1. Flowchart depicting the main steps of the simulation procedure used in the present study.**

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and paired-gear methods [18, 19]. However, such methods are not appropriate for industry-collected data, since they can interfere with the fishing activities. Therefore, it is relevant to address this issue using the catch comparison method. Furthermore, by understanding the trade-offs between sampling effort and gain in information, one can define the number of individuals needed to achieve a given accuracy, and thus avoid excessive data collection.

## Material and methods

In the present study, we investigate how many fish need to be length measured to correctly assess the catch performance of one gear in relation to another in a twin-trawl setting. A theoretical approach was chosen to investigate this topic, where catch comparison data were simulated based on experimental data. To facilitate the description of the different steps used in this simulation study a flowchart is presented in Fig 1. Since the study is solely based on simulated data there were no ethical concerns and thus no permits were required.

### Estimating catch comparison and catch ratio curves

To compare the performance of a new trawl to an existing one, the number of individuals of each length class caught in each codend was used to evaluate the length-dependent relative catching efficiency of both gears (step 4 in Fig 1). This was done by calculating the catch comparison rate, $CC_l$, using the following equation:

$$CC_l = \frac{nt1_l}{nt1_l + nt2_l} \tag{1}$$

where $nt1_l$ is the number of fish of length $l$ of the given species collected in the codend of the test gear and $nt2_l$ is the number collected in codend of the standard (baseline) gear. $CC_l$ ranges from 0.0 to 1.0, where a value of 0.5 implies that both gears have equal catch efficiency for a specific length, on the condition that both gears are fishing equally. One drawback of the catch comparison rate is that it is not possible to immediately infer the relative catch efficiency of the new gear compared to the standard gear. Alternatively, catch ratio, $CR_l$, provides such information by comparing directly the catch efficiency at length for both gears [20]:

$$\mathrm{CR}_l = \frac{nt1_l}{nt2_l} \tag{2}$$

where a $CR_l$ value of 1 means the catch efficiency for both gears, at length $l$, are equal. Thus, a $CR_l = 1.25$ would mean that the test gear caught on average 25% more at length $l$ than the standard gear. In contrast, a $CR_l = 0.75$ would mean the test gear caught 25% less at length $l$ than the standard gear. $CR_l$ ranges from 0 and any positive value. Therefore, in this study, catch ratio was chosen as the relative catch efficiency descriptor.

In catch comparison analyses, $CC_l$ is often modelled following the formula [21]:

$$CC(l,v) = \frac{\exp(f\ (l, v_0, \ldots, v_k))}{1 + \exp(f\ (l, v_0, \ldots, v_k))} \tag{3}$$

where $f$ is a polynomial of order $k$ with coefficients $v_0$ to $v_k$ where $v = (v_0,\ldots,v_k)$. $f$ was considered up to an order of 4 with parameters $v_0$, $v_1$, $v_2$, $v_3$ and $v_4$. Leaving out one or more of the parameters $v_1,\ldots,v_4$ led to an additional 31 models considered as potential models for the catch comparison function $CC(l,v)$. The final model selection was determined through a multi-model inference approach [22]. In this approach, rather than choosing the "best model" fit based on the Akaike's Information Criterion (AIC) value [23], the models are weighted by their respective AIC values. Here, all models where the difference between the respective AIC values and the lowest AIC value are no larger than 10, are used [24]. This method allows for an overall best estimation of the parameters of the model and their associated uncertainties. To estimate the catch ratio curves, Eq (1), Eq (2) and Eq (3) were combined in order to obtain the catch ratio curves directly from the catch comparison curves [20]:

$$\mathrm{CR}(l,v) = \frac{\mathrm{CC}(l,v)}{1 - \mathrm{CC}(l,v)}. \tag{4}$$

The Efron percentile 95% confidence intervals (CI) for the catch comparison and catch ratio curves were estimated using the bootstrapping method described by Efron [25]. A total of 1000 single bootstrap iterations with replacement were performed on each sample for each sampling effort level (described below) to estimate the 95% confidence intervals around the respective catch comparison and catch ratio curves (step 5 in Fig 1). A significant difference between the selective performance of the test and baseline gears occurs when either the upper or the lower limit is under or above the values for equal performance of the gears. These values are 0.5 and 1.0 for the CC and CR curves, respectively. The catch comparison and catch ratio analyses described above were performed using the statistical analysis software SELNET [26].

## Estimating uncertainties associated to each sampling effort level

In this study, relative uncertainties (henceforth, uncertainties) were used to directly compare the uncertainty associated to the $CR(l,v)$ obtained from the different sampling levels (step 6 in Fig 1). These uncertainties were calculated for each length class by using the ratio between the 95% CI range and the catch ratio value obtained from the original data (described below). The average uncertainty for each length class and sampling level was used to define the expected uncertainty for each length class and sampling level. Subsequently, the relationships between the uncertainties within a specific length class and sampling effort were modelled using power models, since this was the expected behaviour for this relationship [18], using the following equation:

$$\hat{U} = a \times n^{b} \tag{5}$$

where $\hat{U}$ is the uncertainty for each length class, $a$ and $b$ the parameters for the respective power models and $n$ the sampling level. Since the objective of this study was to understand the relationship between uncertainties and the total number of individuals sampled, and not the relationship between uncertainties and the number of individuals sampled in a specific length class, the total number of individuals per sample $n$ was used. Regarding the fitting process of the power models, the model error distribution (additive vs. multiplicative) determines which model fitting method is more appropriate (linear regression on log-transformed data vs. non-linear regression on raw data; [27]). Therefore, we evaluated the error distribution following the approach suggested by Xiao *et al*. [27]. The analysis showed that the assumption of multiplicative log-normal error was better supported (results not shown), thus the power models were estimated by fitting a linear regression to the log transformed values. The coefficient of determination ($R^2$) was used to evaluate the quality of the power model fits. This value was directly obtained from the linear model function within the statistical package "*stats*" implemented in the R software [28].

## Determining the minimum sampling effort needed

Considering that the aim of this study is to propose a sampling effort which can facilitate the involvement of the industry in the gear development and testing stages, a range of values is defined. The range defined aims to ensure that the relative performance of the new gear would be, in most cases, correctly evaluated while ensuring that excessive sampling is avoided. Firstly, the lower bound of the sampling range was based on the cases where the small sample sizes conform with the results observed in the full dataset, i.e. when a significant effect in the full dataset was also observed in the smaller sample size. Secondly, the upper bound of the sampling range was defined based on the trade-off between sampling effort and the decrease in uncertainties around the catch comparison curves. For example, when an increase in sampling effort (measuring 100 more individuals) does not lead to a considerable improvement (>5%) in uncertainty.

## Simulated data from sea trials

In order to achieve the objective of this study, and due to the large amount of data required, it was necessary to simulate random samples of catch comparison data with different total numbers of sampled individuals (sampling effort levels). The original dataset was raised by a factor of 50 (step 2a in Fig 1). This step allowed us to simulate the random subsamples without replacement for the sampling levels larger than the original datasets, while maintaining the original catch structure. A second set of catch comparison data was simulated assuming a uniform catch structure, where all considered length classes had a total of 10000 individuals (step 2 in Fig 1). By simulating a uniform catch structure, the effect of the catch structure can be better understood. Furthermore, using the same catch structure for all considered species removed its effect from the analysis, and thus allowed for other potential factors to be better understood. Similar to the raising of the originals datasets, the number of individuals per length class was chosen to allow the simulation of random samples without replacement for the larger sampling levels. The split between individuals caught in the standard and test gears in the uniform catch structure datasets was calculated based on the $CC_l$ values per length class in the original dataset and by applying Eq (1). The same sampling levels were chosen for both simulated catch distributions, and ranged from a total of 100 to 10000 sampled individuals, with increments of 100 individuals from 100 to 2500 individuals; increments of 250 from 2500 and 5000 individuals; and increments of 1000 from 5000 to 10000 individuals (step 3 in Fig 1). For each sampling level and catch structure, 100 random samples were simulated with an equal number of sampled individuals per gear [29], resulting in a total of 16000 simulated samples. Moreover, subsampling factors were obtained by calculating the ratio between total number of individuals of the subsample per gear and the total number of sampled individuals in the simulated datasets. Each of the 100 random samples per sampling level and catch structure represents the pooled data of a single catch comparison trial with a given total number of sampled individuals. The data simulations described above were carried out using R [28].

### Sea trial data

To ensure that the simulated samples were as realistic as possible, the random subsamples were simulated based on actual catch comparison data (step 1 in Fig 1). The data used for this study were initially reported by Krag *et al.* [17] and collected as part of a scientific gear selectivity trial in the North Sea. In this sea trial, the test gear had two common trawl modifications: a topless trawl and a square mesh escape panel. A twin-rig trawl setup was used, where the modified gear was towed in parallel to the standard gear, and the total number of individuals caught per length class was collected for both gears.

The present study included data for cod (*Gadus morhua*) and Norway lobster (*Nephrops norvegicus*), since both are important commercial species and a change in the selective performance of the new gear was expected for one species (cod) but not the other (Norway lobster) [17]. Moreover, for an easier visualisation and interpretation of the results, 3 representative length classes were chosen for both species: one where the number of individuals was abundant, one where the number of individuals was few, and one with intermediate values (40, 65 and 90 cm for cod and 35, 45 and 65 mm carapace length for Norway lobster).

## Results

The catch comparison and catch ratio analyses of the simulated data (16000 samples) took an average of 12 central processing unit (CPU) hours per sample, adding up to approximately 192000 CPU hours. The average speed of the CPUs used for this analysis was around 2.0 GHz.

The catch comparison and catch ratio results from the original data for cod and Norway lobster are shown in Fig 2. A significant length-dependent effect for both species was observed. The test gear caught significantly less cod between 23 and 84 cm, since for those length classes the catch comparison and catch ratio were significantly lower than 0.5 and 1.0, respectively (Fig 2A and 2B). Furthermore, a significant increase was observed for cod equal to or smaller than 15 cm. For Norway lobster, a significant increase was detected for individuals ($< = 38$ mm), while no significant effect was found for individuals larger than 38 cm (Fig 2C and 2D).

The catch ratio values for cod from the simulated data were significantly different from 1.0 for the length classes of 40 and 65 cm in the observed catch structure (Fig 3A and 3B). The significant difference was observed even for the smallest sample size of only 100 individuals (Fig 3A and 3B). However, no significant effect was observed in the 90 cm length class, irrespective of the number of individuals measured (Fig 3C). For the uniform catch structure, the three chosen length classes for cod showed similar results. Furthermore, the CIs show a similar behaviour across all length classes, where the total range became narrower at smaller sample sizes than in the observed catch structure (Fig 3D, 3E and 3F).

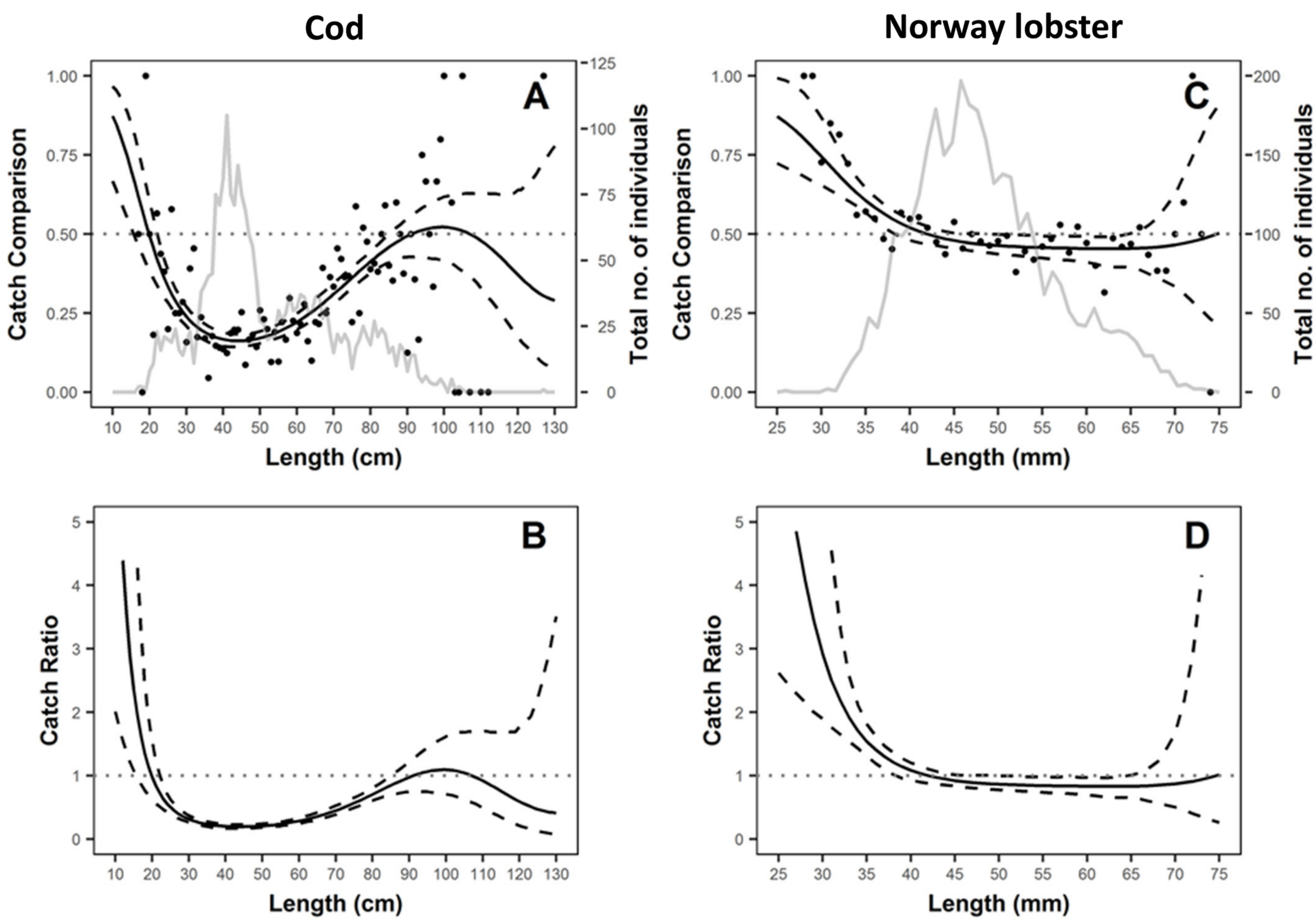


**Fig 2. Estimated catch comparison and catch ratio curves (solid black line) and 95% confidence intervals (broken black lines) for cod (A and B, respectively), and for Norway lobster (C and D, respectively).** Dotted grey lines represent when both gears are fishing equally efficient. Grey solid lines in A and C represents the catch length structure for cod and Norway lobster, respectively.

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For Norway lobster, catch ratios were significantly different from 1.0 for the 35 and 65 mm length classes (Fig 4A and 4C), while no significant difference was observed for the 45 mm length class (Fig 4B). For the 35 mm length class, a significant difference was observed at smaller sample sizes (a total sample size of ~350 individuals), while for the 65 mm length class a significant difference was observed only for larger sample sizes (a total sample size of ~3250 individuals). The CIs observed for Norway lobster with a uniform catch structure showed a similar behaviour to those observed for the original catch structure (Fig 4D, 4E and 4F). However, the total range became narrower at smaller sample sizes when compared to the CI ranges of the observed catch structure. This is similar to what was observed for cod.

In Table 1, the different parameters and the coefficients of determination ($R^2$) for the different power models are shown. In general, the different fitted curves showed high $R^2$ values, ranging from 0.88 to 1, with the lowest values observed in the tail areas of the chosen length classes for both species. This was more evident for the original catch structure. The curve describing the uncertainty for 90 cm cod from the original catch structure showed a tendency to predict with a systematic bias to higher values. However, this curve is also the curve with the lowest $R^2$, thus indicating that the coefficient of determination was able to sufficiently describe

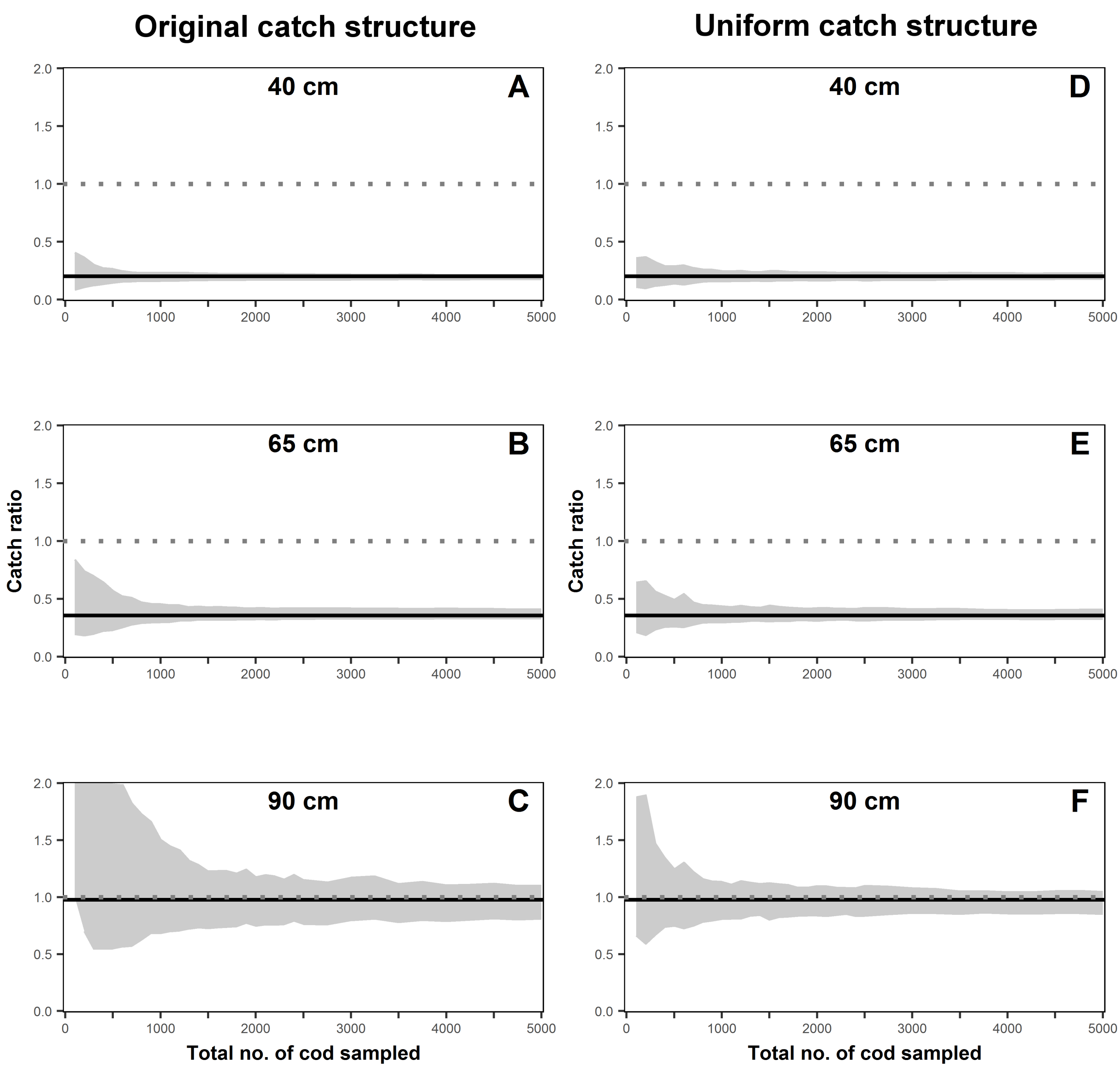


**Fig 3. Effect of sample size on catch ratio confidence intervals (grey band) per length class for cod (40, 65, 90 cm).** The confidence intervals shown in fig A to C are for the observed catch structure and from D to F are for the uniform catch structure scenario. The solid black line and the dotted grey line define for a specific length class the original catch ratio and when both gears are fishing equally efficient (catch ratio equal to 1), respectively.

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the quality of the fits of the power model curves to the uncertainty data. Furthermore, there is a clear harmonisation of the quality of the fits for both species in the case of the uniform structure. A similar tendency was also observed for both parameters of the power models (*a* and *b*). For both species, the highest values (thus, higher uncertainties) were observed in the tail areas, but when the uniform catch structure was applied this difference was substantially reduced.

The uncertainty curves (Fig 5A and 5B) for the three length classes for cod, and the effect on uncertainty when adding an extra 100 individuals to a given sample size (Fig 5C and 5D)

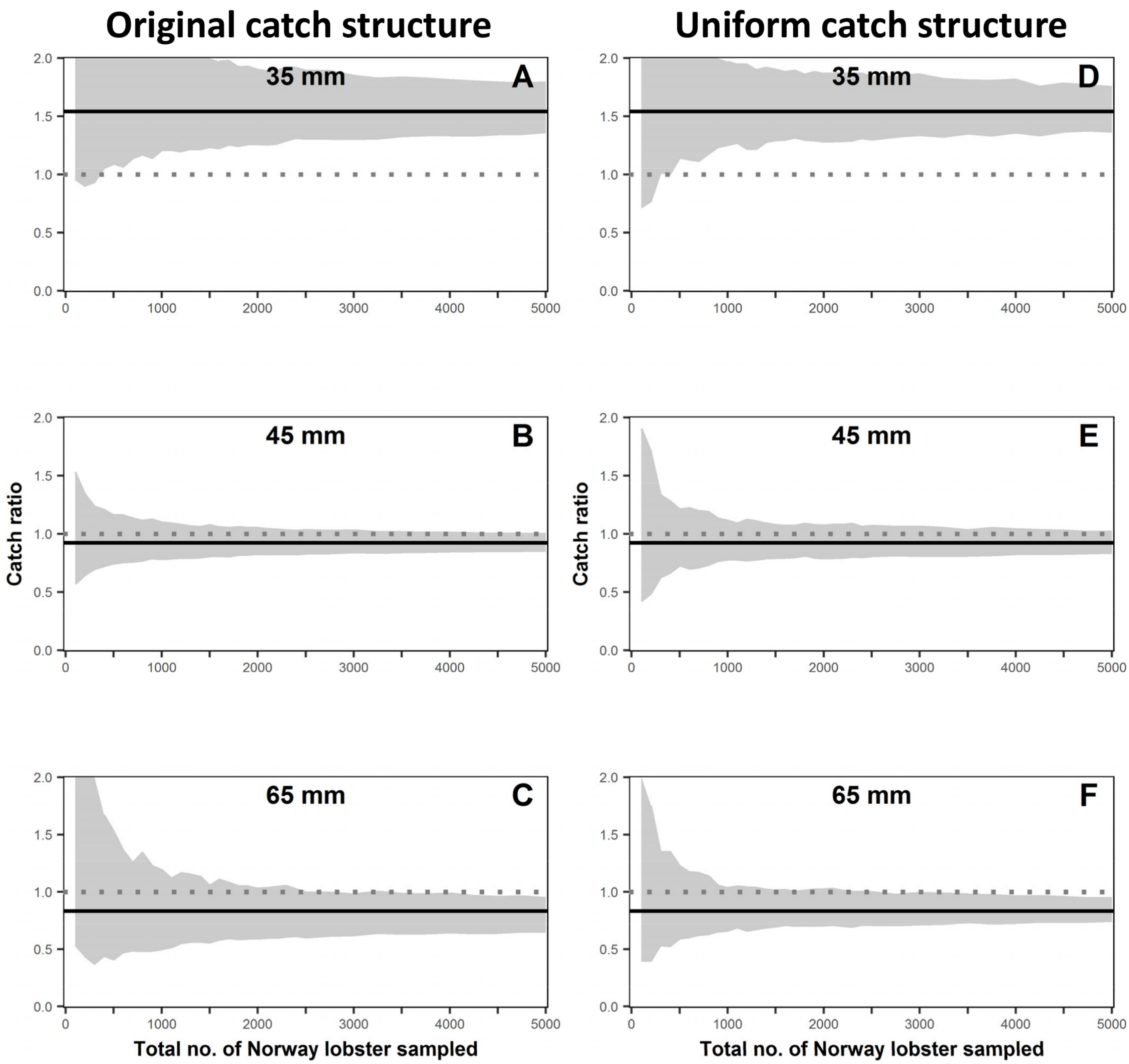


**Fig 4. Effect of sample size on catch ratio confidence intervals (grey band) per length class for Norway lobster (35, 45, 65 mm).** The confidence intervals shown in fig A to C are for the observed catch structure and from D to F are for the uniform catch structure scenario. The solid black line and the dotted grey line define for a specific length class the original catch ratio and when both gears are fishing equally efficient (catch ratio equal to 1), respectively.

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show a clear relationship between the observed total sample sizes and the associated uncertainties. Regardless of the length class or catch structure, the uncertainties decreased with an increased sample size. Since the uncertainties follow a power-law, the slopes of the curves were much steeper for small sample sizes than for larger samples sizes. Furthermore, a relationship between the uncertainties and the strength of the data at a given length class was detected for the observed catch structure (Fig 5A). This relationship was not evident for the uniform catch structure (Fig 5B). The differences between the uncertainty curves were substantially reduced,

**Table 1. Power model parameters (*a* and *b* from equation 6) for the relative uncertainties and goodness of fit per sampling level, length class, species, and catch length structure.** Coefficient of determination ($R^2$) represents the quality of the fit and ranges from 0 to 1, where 1 is a perfect fit.

| | | Original catch structure | | | Uniform catch structure | | |
|---|---|---|---|---|---|---|---|
| **Species** | **Length class*** | ***a*** | ***b*** | $R^2$ | ***a*** | ***b*** | $R^2$ |
| **cod** | 25 | 185.36 | -0.76 | 0.90 | 18.09 | -0.52 | 0.96 |
| | 30 | 90.15 | -0.73 | 0.88 | 14.92 | -0.49 | 0.95 |
| | 35 | 23.62 | -0.58 | 0.97 | 13.93 | -0.48 | 0.96 |
| | 40 | 16.04 | -0.54 | 0.97 | 12.44 | -0.46 | 0.96 |
| | 45 | 14.49 | -0.53 | 0.96 | 10.84 | -0.45 | 0.96 |
| | 50 | 19.37 | -0.57 | 0.96 | 9.75 | -0.45 | 0.96 |
| | 55 | 26.53 | -0.60 | 0.95 | 9.61 | -0.45 | 0.95 |
| | 60 | 29.47 | -0.60 | 0.94 | 10.18 | -0.46 | 0.94 |
| | 65 | 27.82 | -0.59 | 0.93 | 11.02 | -0.46 | 0.93 |
| | 70 | 27.13 | -0.58 | 0.92 | 11.61 | -0.47 | 0.92 |
| | 75 | 39.84 | -0.63 | 0.93 | 11.67 | -0.47 | 0.92 |
| | 80 | 54.46 | -0.66 | 0.92 | 11.20 | -0.48 | 0.92 |
| | 85 | 124.26 | -0.74 | 0.92 | 10.58 | -0.48 | 0.92 |
| | 90 | 200.19 | -0.78 | 0.88 | 10.70 | -0.48 | 0.93 |
| **Norway lobster** | 30 | 1381.48 | -0.82 | 0.94 | 34.72 | -0.58 | 0.94 |
| | 35 | 39.19 | -0.59 | 0.97 | 22.71 | -0.53 | 0.95 |
| | 40 | 11.37 | -0.49 | 1.00 | 14.05 | -0.49 | 0.96 |
| | 45 | 9.83 | -0.49 | 1.00 | 12.79 | -0.49 | 0.96 |
| | 50 | 10.72 | -0.47 | 1.00 | 14.38 | -0.50 | 0.96 |
| | 55 | 14.95 | -0.50 | 0.99 | 13.92 | -0.50 | 0.96 |
| | 60 | 25.72 | -0.54 | 0.98 | 14.84 | -0.51 | 0.96 |
| | 65 | 38.69 | -0.55 | 0.98 | 19.07 | -0.52 | 0.96 |
| | 70 | 12627.31 | -1.13 | 0.89 | 34.63 | -0.59 | 0.89 |

*Please note that length classes for cod are in cm (total length) and for Norway lobster in mm (carapace length)

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showing a higher overlap of the observed uncertainties and their respective curves (Fig 5B). Moreover, the curves illustrating the effect of adding an extra 100 individuals showed similar patterns (Fig 5C and 5D). A large decrease in uncertainties was observed for sample sizes smaller than 250 individuals, while at sample sizes greater than 1000, the decrease was limited. As for the uncertainty curves, removing the effect of catch structure resulted in an overlap of the 3 different curves (Fig 5D), highlighting furthermore the importance of data strength at a given length class.

The uncertainty curves for the three length classes for Norway lobster, and the effect on uncertainty when adding an extra 100 individuals to a given sample size are shown in Fig 6. Here, despite the catch ratio values at the given length classes being different for cod, similar results were observed. The uncertainties decreased with an increase in total sample size (Fig 6A and 6B); with the differences between the uncertainties curves being less pronounce for the uniform catch structure. The curves illustrating the effect of adding an extra 100 individuals showed very similar behaviour to those observed for cod (Fig 6C and 6D), where the overlap of the curves for the uniform catch structure was also pronounced (Fig 6D).

Using the length classes shown in Table 1, the average number of individuals required to obtain a given decrease in uncertainty by adding an additional 100 is shown in Table 2. A similar tendency for both species was observed; removing the effect of catch structure by using a uniform distribution reduced the average sample sizes obtained for each level of decrease in

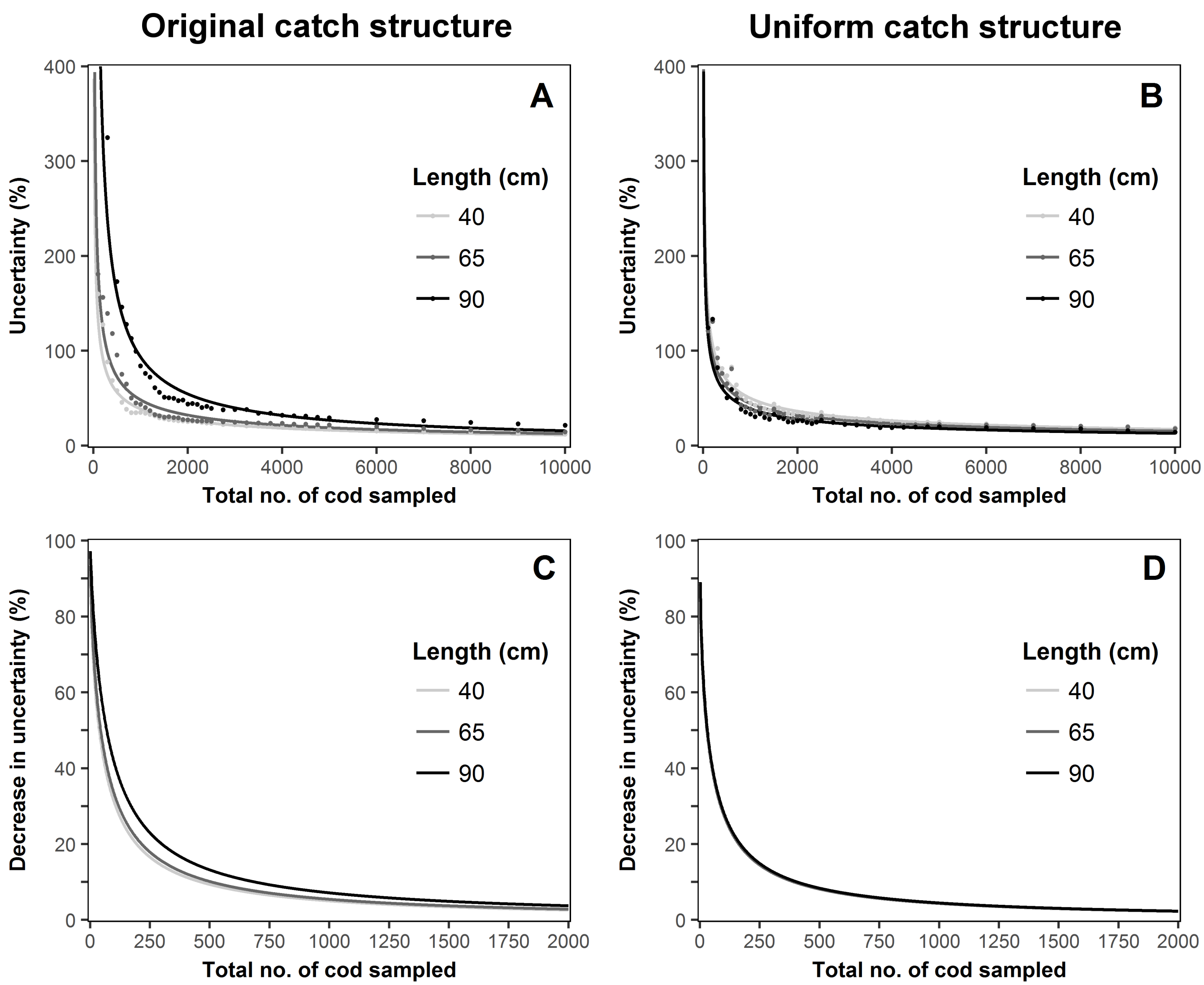


**Fig 5. Cod uncertainty curves for the observed catch structure (A) and uniform catch structure (B); and decrease in relative uncertainty when sampling 100 more individuals for the observed catch structure (C) and uniform catch structure (D).** Points in fig A and B represent the observed relative uncertainties.

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uncertainty, and the variability between length classes. Moreover, the values obtained from the original and uniform catch structures for both species are relatively similar, although Norway lobster showed a higher variability than cod. Based on the results and the methodology used to define the lower and upper bounds, a sampling effort of 500 to 1000 individuals is proposed for both species and catch structures.

## Discussion

To achieve the objectives of the EU landing obligation, and those specified in the proposal for a new technical measures regulation (inter alia, flexibility and stakeholder involvement), greater flexibility in the number of gears able to be used in the fisheries is needed [2, 4]. A possible cost effective way to achieve these objectives is to have the industry involved in the development and testing of new gears, as well as the collection of data describing the selectivity of the new gears in relation to one which is legislated. However, to have a successful industry-

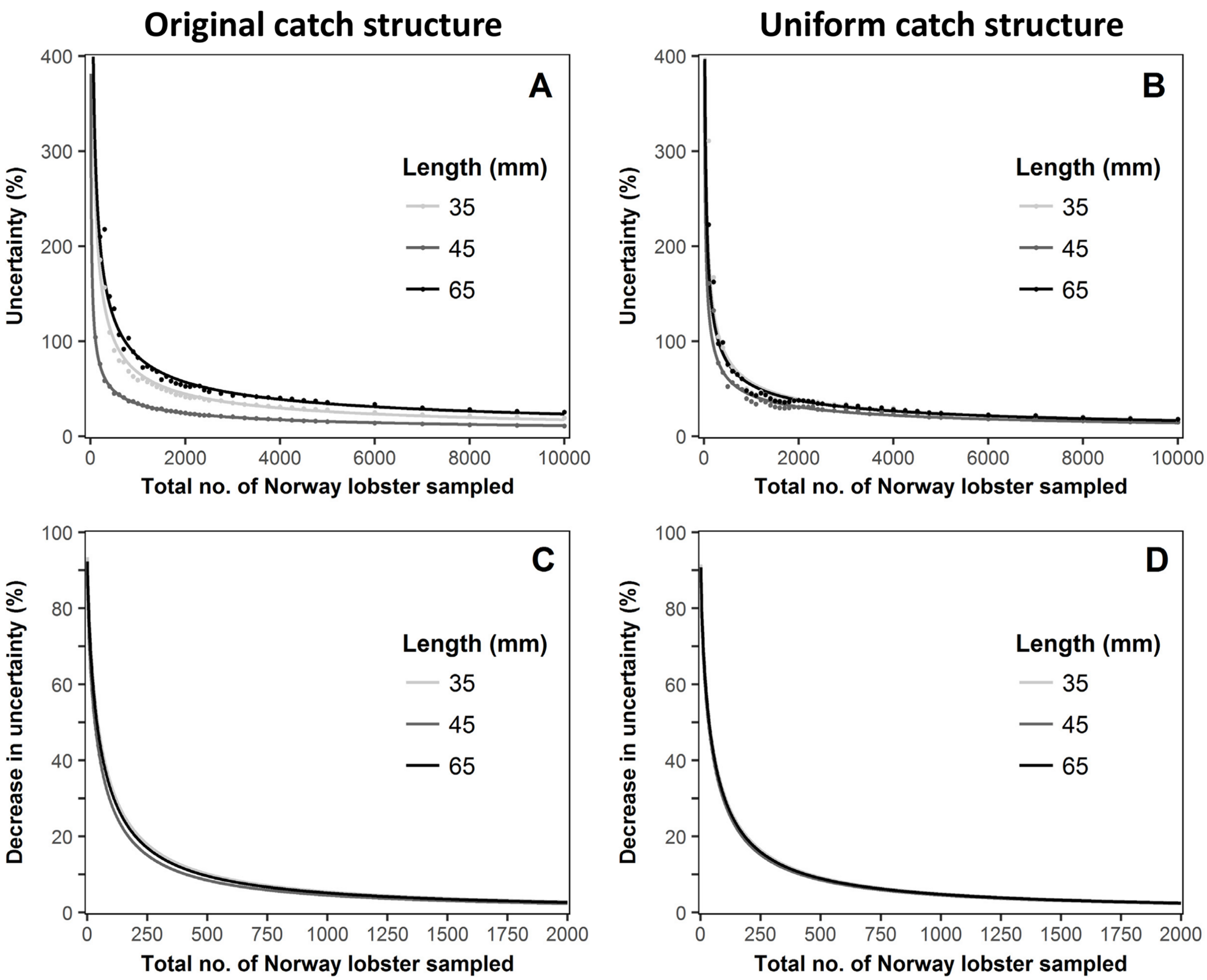


**Fig 6. Norway lobster uncertainty curves for the observed catch structure (A) and uniform catch structure (B); and decrease in relative uncertainty when sampling 100 more individuals for the observed catch structure (C) and uniform catch structure (D).** Points in fig A and B represent the observed relative uncertainties.

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collected data programme, those involved need to be burdened as little as possible as they have another objective, which is to carry out an economically viable fishery. Our results demonstrate that it is possible for fishermen to collect catch comparison data with a level of accuracy which makes it possible to correctly evaluate the performance of a new gear. With a relatively small sample size (500 to 1000 individuals per species) it is possible to assess the performance of a new fishing gear with an acceptable degree of uncertainty. These values are in the same range as those found by Herrmann *et al*. [18] for the estimation of selectivity curves using the paired-gear method; a method which is comparable to the catch comparison method. Considering that the total sample size per species is obtained throughout the testing phase, which usually has a duration of a couple of weeks, fishermen would need to sample relatively few individuals, per species, gear and haul, to obtain an acceptable degree of uncertainty. Furthermore, as the objective of a fishing gear selectivity trial is to address a specific issue in a fishery, the total number of sampled species is typically low, 2–3 species, including target and

**Table 2. The number of individuals sampled and the associated decrease in uncertainty when measuring 100 more individuals.** Mean values for all length classes considered and their respective standard deviations (in parenthesis) are presented.

| | cod | | Norway lobster | |
|---|---|---|---|---|
| **Decrease in uncertainty** | **Original catch structure (*n*)** | **Uniform catch structure (*n*)** | **Original catch structure (*n*)** | **Uniform catch structure (*n*)** |
| **50%** | 51 (±11) | 30 (±2) | 49 (±29) | 36 (±5) |
| **40%** | 81 (±16) | 51 (±3) | 79 (±41) | 60 (±7) |
| **30%** | 133 (±23) | 89 (±5) | 129 (±60) | 102 (±10) |
| **25%** | 175 (±29) | 119 (±6) | 170 (±76) | 137 (±13) |
| **20%** | 238 (±37) | 165 (±8) | 231 (±98) | 188 (±17) |
| **15%** | 343 (±52) | 243 (±11) | 334 (±135) | 274 (±23) |
| **10%** | 555 (±80) | 399 (±16) | 540 (±209) | 448 (±36) |
| **5%** | 1190 (±164) | 870 (±33) | 1159 (±429) | 971 (±73) |
| **2%** | 3096 (±416) | 2283 (±85) | 3018 (±1090) | 2539 (±186) |
| **1%** | 6274 (±837) | 4640 (±172) | 6117 (±2191) | 5154 (±374) |

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unwanted species. Therefore, on a haul level, the burden of collecting the required data should be minimal for the fishermen.

As a consequence of the low number of individuals required to be measured, the uncertainties around the average catch comparison curves are relatively large. The proposed number of individuals to measure is based on the analysis of the uncertainties associated with the different sampling efforts. As the results show, the uncertainties associated with the sampling effort follow a power law, whereby the differences between the overall uncertainties will be far greater for smaller sample sizes than for larger sample sizes. This behaviour of the uncertainties in relation to sample size was expected and confirmed by the overall quality of the power model fits (lowest $R^2$ was 0.88) and was also described in Herrmann *et al.* [18]. Despite the proposed sampling range (500 to 1000 individuals) leading to potential large uncertainties, we consider it acceptable to use these for a preliminary assessment of the performance of a gear. However, more fish would need to be measured to reduce these uncertainties where the data are used for management purposes.

An additional aspect which needs to be considered is whether or not these results are applicable to other species and gear designs. Here we chose two species which are very different morphologically, and had very different observed population structures. The same trends in uncertainties were observed, e.g. large increases in uncertainties for the length classes with less data (tail area of the curves for the catch structures) for both species. To disclose the cause of this, uniform catch structures were simulated, which showed that the increase in uncertainties around the tails of the curves was caused by the low number of individuals measured at those length classes. Despite these differences, the uncertainty curves for both the observed and simulated catch structures were very similar to one another. Therefore, the results are applicable to different catch structures, and hence, species.

Despite the method being relevant to all species and areas, the difference in selectivity between the standard and test gears will define the magnitude of the effect and how early on in the sampling process an effect becomes evident. For example, in this study we looked at two different species, a target species (Norway lobster) where we did not expect to see an effect and a bycatch species (cod) where an effect was expected. For a species where no effect is expected, it should not matter if the entire catch is measured, as no effect should be present. However, for a species where a large effect is expected, one would anticipate the effect to be detectable early on in the sampling. This was the case observed in our study, where an effect for cod was detected after sampling only 100 individuals, while no effect was observed for Norway lobster at all sampling levels. This means that the magnitude of the effect is considerably more important than the species' catch structure.

The importance of the magnitude means that if there is only a small effect of the new gear it might be difficult to detect a significant effect with so few individuals. However, when the objective is to define which gears should be taken to a full scientific trial, one would only want to choose those gears where a substantial effect can be obtained. Hence, this is not considered to be a major shortcoming of the method presented herein. Furthermore, a strength of this approach is that it is iterative, meaning that it is possible for the fishermen to collect additional data which can be analysed along the way. An additional strength of this approach is that if the modification which has been developed and tested does not achieve the desired outcome, additional modifications to the gear can be made without the need of an extensive gear selectivity trial.

The analysis presented herein is based solely on catch comparison data from a trawl fishery. Despite this, the methodology and findings may be applicable to different types of fisheries. The analysis presented here is based on length-dependent catch comparison data, where the performance of one gear is compared to a baseline. Therefore, the same approach should be applicable in different types of fisheries, for example, longline fisheries comparing different hook types or sizes, or creel fisheries with different mesh size. Hence, the findings of this paper should also be relevant to other types of fisheries.

In the present study, we do not consider between-haul variation, as an assumption of such variation may not be representative for other catch comparison experiments. Therefore, the range proposed here can be considered the absolute minimum number of individuals to measure, since one would expect the uncertainties to be larger when accounting for between-haul variation. However, since this is a first attempt at quantifying the minimum sampling efforts required to correctly document a gear's relative selectivity, the values presented herein are still applicable as guidelines.

To be able to fully evaluate the results presented herein they should be benchmarked against those obtained from scientific trials. For example, are the trends observed in the industry-collected data the same as those observed in the scientific trial? This will help disclose whether or not these data can be used for a preliminary evaluation of a gears relative selectivity, and to what extent they can be used.

## Conclusion

This study shows that it is possible for fishermen to collect quality data on the performance of a new gear without affecting their main activity. This can help facilitate the needed flexibility in gear development which is currently lacking under the existing EU management system. By having the industry develop and test their own gears, as well as being involved in the collection of data, one increases the amount of potential solutions available to address the different issues emerging in the fisheries. From a list of potential solutions, the most promising and/or relevant ones can then be selected for a thorough scientific test in order to introduce the new gears into legislation. Here we have shown that it should be possible for the industry to collect relevant data to describe the relative selectivity of a new gear, where the guidelines presented herein can potentially be used in any fishery and for any gear. This new framework proposed here defines a new way of securing a fast and iterative development of thoroughly tested and well-documented fishing gears with minimal time and economic outlay.

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**Funding acquisition:** Tiago Veiga-Malta, Jordan Feekings.

**Investigation:** Tiago Veiga-Malta.

**Methodology:** Tiago Veiga-Malta, Bent Herrmann.

**Project administration:** Jordan Feekings.

**Resources:** Ludvig Ahm Krag.

**Software:** Bent Herrmann.

**Supervision:** Jordan Feekings, Ludvig Ahm Krag.

**Validation:** Tiago Veiga-Malta, Bent Herrmann.

**Writing – original draft:** Tiago Veiga-Malta, Jordan Feekings.

**Writing – review & editing:** Tiago Veiga-Malta, Jordan Feekings, Bent Herrmann, Ludvig Ahm Krag.

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# Paper 2

# Industry-led fishing gear development: Can it facilitate the process?

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## Abstract

In the reformed technical measures regulation, the European Union proposed a greater involvement of the fishing industry in the different managerial aspects of fisheries. However, having the industry as a main actor in gear development presents a new suite of challenges. The industry, while addressing an issue in the fishery, can modify several aspects of a fishing gear simultaneously, without considering that some of those changes might have opposing effects. Here we present a case study where a codend, with several modifications, was developed by the industry for the Baltic cod trawl demersal fishery. Our results, based on cumulative catch distribution, catch comparison, and usability indicators, showed that the industry can successfully develop gears with more suitable catch profiles than the one currently used. However, one modification to the codend, the increased circumference, had the opposite effect than expected by the industry. Having the industry as the main driver in the development of new fishing gears can facilitate the development of a larger number and more specialized technical solutions. However, an early and continuous involvement of scientists in the process is crucial, as it ensures that unnecessary and adverse modifications are not made to the gear.

## Keywords

Industry-led; fishing gear development; Baltic Sea; gear selectivity; fisheries management

## Introduction

In fisheries management, one of the most widely used technical measures to achieve different managerial objectives is the implementation of more selective fishing gears (Graham *et al.*, 2007; Enever *et al.*, 2009; Condie *et al.*, 2014). Despite their extensive use, there are examples where the implementation of new or modified fishing gears did not have the desired effect (e.g. Krag *et al.*, 2016). The main motivation for the industry to negate the selectivity of a newly legislated gear stems primarily from the reduction or perceived reduction in target catch, resulting in short-term economic losses (Suuronen and Sardà, 2007; Suuronen *et al.*, 2007; Krag *et al.*, 2016). This negation of selectivity can occur when the technical solutions that are available for use within an entire fishery and management area are perceived by the industry as inadequate, e.g. the size selectivity of the gear does not match the minimum conservation reference size (MCRS) of the target species (Suuronen *et al.*, 2007). Under the European Union (EU) Common Fisheries Policy (CFP) of 2013, the management setting has changed to one where technical solutions can play a much larger role in achieving sustainability objectives.

Under the 2013 CFP, all catches of quota regulated listed species are to be counted against the quota, formally known as the landing obligation (LO), and once a species quota is fished that species has the possibility to choke the fisheries (European Union, 2013). Therefore, unwanted catches now have a direct monetary cost to the industry, directly linking selectivity to economy in the fisheries. The risk of a species choking a fishery can occur at different times throughout the year. Consequently, technical measures need to be developed to resolve these issues as they arise, where the measures will be dependent on the species which is/are choking the fishery. The need for a larger number of more specific technical solutions is something which is suggested in the proposed technical measures framework (Eliasen *et al.*, 2019). Furthermore, effective solutions will need to be implemented relatively quickly. This is something which has been acknowledged in the 2013 CFP with the introduction of regional groups, with them being given the mandate to implement delegate acts (Eliasen *et al.*, 2019).

One way to potentially increase the number and acceptance of new technical measures, particularly new fishing gears, is to not only have the industry involved in the development and testing of those fishing gears (e.g. Suuronen and Sardà, 2007) but rather lead the entire process (ICES, 2018a). The increased involvement of industry in the identification, development and testing of new gears, as well as in the documentation of their selective performance is something which numerous European institutes (Denmark, Sweden, Scotland, The Netherlands, Belgium and England) are working on (ICES, 2018a) and has theoretically been demonstrated to be possible (Veiga-Malta *et al.*, 2018). Veiga-Malta *et al.* (2018) demonstrated that it is possible for the fishing industry to collect preliminary selectivity data on the performance of a new gear design. The industry could therefore be able to lead the entire development process, from identifying the problems, developing and testing multiple solutions in parallel, to collecting the data necessary for a preliminary documentation of the gear's performance. Such a system changes the way gears are developed, giving the industry a much larger and more proactive role in the process. However, this can result in a new suite of challenges for managers and scientists.

In this study, we evaluate the effect on size selectivity and catch pattern of an industry-developed gear modification and investigate if it met the industry's objective. We used a case study from the Baltic Sea cod (*Gadus morhua* Linnaeus, 1758) demersal trawl fishery, the most important demersal fishery in the Baltic Sea (ICES, 2018b). The industry developed a codend following the development process outlined above and described in Veiga-Malta *et al.* (2018). The main selectivity process in a standard demersal trawl without any by-catch reduction device occurs in the codend (Wileman *et al.*, 1996). Thus, to adjust the trawl selectivity, several parameters of the codend can be modified, such as, mesh shape (e.g. Campos *et al*., 2003; Herrmann *et al.*, 2007), mesh size (e.g. Herrmann *et al.*, 2009; Wienbeck *et al.*, 2011; Wienbeck *et al.*, 2014), codend circumference (e.g. Reeves *et al.*, 1992; Graham *et al.*, 2009; Herrmann *et al.*, 2015), twine material and thickness (e.g. Ferro and O'Neill, 1994; Tokaç *et al.*, 2004), and through the use of lastridge ropes (e.g. Hickey *et al.*, 1993; Lök *et al.*, 1997). The industry developed a codend with several of these parameters modified. Their aim was to adjust the selectivity of the gear to better match the MCRS of 35 cm for Baltic cod. Furthermore, according to the industry, the two gears currently legislated, T90 120 mm and BACOMA 120 mm (EU Regulation no. 686/2010), are too selective (e.g. a large loss of individuals above the MCRS) due to changes in the cod population structure in recent years, something which has occurred due to the increased fishing pressure on larger cod (Svedäng and Hornborg, 2014; Svedäng and Hornborg, 2017). Finally, based on this case study, we identify and discuss the potential advantages and challenges of industry-led fishing gear development.

## Material and Methods

The codend developed by the industry had four modifications compared to the one currently used by the fleet, a T90 120 mm codend with 50 meshes in the circumference; a larger circumference, smaller mesh size, shortened lastridge ropes, and twine made of polyethylene (PE) instead of polyester (PES). A T90 codend is a diamond mesh codend where the meshes are turned 90 degrees, with the intention of keeping the meshes open during the fishing process (Herrmann *et al.*, 2007). Lastridge ropes are ropes that are attached to the selvedges of the codend, that when shortened ensure the meshes remain open during the fishing process (Hickey *et al.*, 1993). Since the codend proposed by the industry had several modifications, we disentangle the effects of the different modifications. Describing and understanding the effects of the individual modifications makes it possible to optimise the performance of the new fishing gear and facilitate its implementation in legislation (Eliasen *et al.*, 2019). Therefore, three consecutive gear selectivity trials were conducted.

The relative size selectivity and catch patterns of the codends tested were compared in each of the three trials. In the first trial, the industry-developed codend, hereby referred to as IND, was compared to the standard T90 codend made from polyester (PES), hereby referred to as PES. In the second trial, IND was compared to the standard T90 codend constructed from polyethylene (PE), hereby referred to as PE. In the third trial, a codend similar to PE but with a larger circumference of 92 meshes around, hereby referred to as LC codend, was compared to PE. For further details on the four codends tested see Table 1.

**Table 1.** Description of the technical specifications of the four codends tested in the sea trials.

| Characteristic | (IND) | (PES) | (PE) | LC |
|---|---|---|---|---|
| **Mesh orientation** | T90 | T90 | T90 | T90 |
| **Nominal mesh size (mm)** | 110 | 120 | 120 | 120 |
| **Measured mesh size (mm)** | 109.1 | 121.4 | 123.1 | 122.8 |
| **Standard deviation** | 2.4 | 1.9 | 2.2 | 2.2 |
| **Codend circumference (no. open meshes)** | 92 | 50 | 50 | 92 |
| **Twine thickness** | 4 mm double | 4 mm double | 4 mm double | 4 mm double |
| **Shortened lastridge ropes** | Yes | No | No | No |
| **Net material** | Polyethylene (PE) | Polyester (PES) | Polyethylene (PE) | Polyethylene (PE) |
| **Codend length (m)** | 10.5 | 8 | 8 | 8 |
| **No. of selvedges** | 2 | 2 | 2 | 2 |
| **Number of mesh in each selvedge** | 4 | 4 | 4 | 4 |

The sea trials were conducted in the Baltic Sea off the coast of Bornholm on board of the commercial vessel R 218 Judith Bechmann (a twin-rig trawler with 25.9 m length and 485 Kw), during $17^{th}$ to $27^{th}$ of June 2017. The fishing grounds were chosen by the skipper based on his experience, so that the size structure of the cod population available to the gears was representative of commercial trips. The vessel was equipped with two identical trawls where the only difference was the codends used. The sea trials were conducted as catch comparison trials (Krag *et al.*, 2014) where two trawls were towed in a twin-rig setting, with the position of the tested codends being swapped every 3-5 hauls, to account for systematic trawl side effects. Towing both trawls in parallel ensures that on a haul-by haul basis both codends tested are subjected to the same varying fishing conditions, population structures and sizes. Additionally, not using covers around the codend ensured that the fishing conditions were kept as similar as possible to commercial fishing conditions. By using this method we are not able to measure the absolute selective of the two gears but only the size selective performance of one gear with respect to the other, also known as relative size selectivity and/or catch ratio (e.g. Sistiaga *et al*. 2015, Santos *et al*., 2016). However, the focus of the study was to assess the selective performance of the industry-developed codend compared to the legislated codend most commonly used in the Baltic cod fishery. Therefore, the catch comparison method was preferred because it allows to operate the vessel under true commercial conditions while providing a direct comparison of the codends tested. Furthermore, the order in which the codends were retrieved was also taken into account by alternating every second haul which codend was retrieved first, the starboard or port side, respectively. The second codend was hanging loosely beside the vessel for approximately 5 to 10 min. All cod caught were length measured and rounded down to the nearest centimetre.

*Statistical analyses*

The number of individuals per length class caught in the different codends in each of the trials was used to evaluate the length dependent relative catch efficiency for cod in the test gears in relation to the baseline gears. Moreover, the number of individuals per length class provides an estimate of the relative size selectivity between the two codends, thus comparing the length-dependent catching efficiency of both gears. The portion of the total catch caught by the test gear was obtained through the use of the catch comparison equation (CC; Krag *et al.*, 2014):

$$\mathrm{CC}_{il} = \frac{\sum_{i=1}^{h} n\mathrm{t}_{li}}{\sum_{i=1}^{h} n\mathrm{t}_{li} + \sum_{i=1}^{h} n\mathrm{b}_{lj}} \tag{1}$$

where $n\mathrm{t}_{il}$ is the number of individuals caught per length class $l$ and haul $i$ in the test codend, and $n\mathrm{b}_{il}$ is the equivalent for the codends used as the baseline in the different trials. The total number of hauls in the trial is represented by $h$. From the catch comparison values obtained experimentally, the length-dependent relative catch efficiency was modelled through the use of the catch comparison function $\mathrm{CC}(l,\boldsymbol{q})$, (Krag *et al.*, 2014):

$$CC(l,\boldsymbol{q}) = \frac{\exp(f\ (l,q_0,\ldots,q_k))}{1 + \exp(f\ (l,q_0,\ldots,q_k))} \qquad (2)$$

where $f$ is a polynomial of order $k$ with coefficients $q_0$ to $q_k$ so $\boldsymbol{q}$ = ($q_0$,…, $q_k$). $f$ was considered up to an order of 4 with parameters $q_0$, $q_1$, $q_2$, $q_3$ and $q_4$. Leaving out one or more of the parameters $q_1$, …, $q_4$ led to 31 additional models that were also considered potential models for the catch comparison function $CC(l,\boldsymbol{q})$. The selection of the final models was based on multimodel inference (Burnham and Anderson, 2002). In this approach, an average of the best models, weighted by their respective Akaike's Information Criterion (AIC) values (Akaike, 1974), is chosen rather than selecting the model with the lowest AIC value. This method allows for an overall better fit of the estimated curves of the model and their associated uncertainties. Here, all models were used where the difference between their respective AIC values and the lowest AIC value was 10 or lower (Katsanevakis, 2006). How well the combined model results fitted the experimental data was evaluated through the *p*-value, residuals deviance and how it relates to the degrees of freedom, and the visual inspection of the residuals distribution (Wileman *et al.*, 1996). The *p*-value expresses the likelihood for obtaining by coincidence a discrepancy equal to or larger than the observed discrepancy between the fitted model and the experimental data, thus the *p*-value should not be <0.05 (Wileman *et al.*, 1996). Moreover, residual deviances and the degrees of freedom should show values within the same order of magnitude (Wileman *et al.*, 1996).

The $CC(l,\boldsymbol{q})$ descriptor does not provides a direct estimate for the relative catch efficiency for both gears, therefore catch ratio was used since it provides such direct comparison and can be easily derived from $CC(l,\boldsymbol{q})$. This direct comparison provides an easier interpretation of results for fisheries managers and fishermen (Veiga-Malta *et al.*, 2018).

$$\mathrm{CR}(l,\boldsymbol{q}) = \frac{\mathrm{CC}(l,\boldsymbol{q})}{1-\mathrm{CC}(l,\boldsymbol{q})} \qquad (3).$$

where $CR$ can have values equal to or higher than 0. A $CR$ value of 1 means the catch efficiency for both gears at length *l* is equal, while a $CR$ equal to 0.5 and 1.5 means that the test gear is catching 50% less or more, respectively, at length *l* for a given species. The CI for the average $CC(l, \boldsymbol{q})$ and $\mathrm{CR}(l, \boldsymbol{q})$ were estimated using a double bootstrap approach. By using this approach, both within and between haul variations were taken into account. A total of 1000 bootstrap iterations were performed to estimate the Efron percentile 95% confidence limits (Efron, 1982) for all relevant length classes.

Because the gear which was used as a baseline in trials 1 and 2 remained the same, it was possible to indirectly assess the effect the net material had on the catch efficiency of cod. This was performed by calculating the ratio between the catch ratio curves obtained from the first and second trials using the following equation:

$$CR(l, \boldsymbol{q})_{PES/_{PE}} = \frac{\mathrm{CR}(l, \boldsymbol{q})_{trial1}}{\mathrm{CR}(l, \boldsymbol{q})_{trial2}} \qquad (4)$$

where in both catch ratio analyses the numerator was the test gear. This simple mathematical manipulation makes it possible to infer the relative size selectivity of the codend made of PES in relation to the codend made of PE.

The 95% confidence intervals (CI) for $CR(l, \boldsymbol{q})_{PES/_{PE}}$ were obtained based on the two bootstrap populations of results (1000 bootstrap repetitions in each) from each CR model estimated for the first and second trials. Since both bootstrap populations were obtained independently and the sampling to obtain those populations of results was performed randomly and independently, a new population of results with 1000 bootstrap iterations was created for $CR(l, \boldsymbol{q})_{PES/_{PE}}$ following (Herrmann *et al.*, 2018):

$$CR(l, \boldsymbol{q})_{PES/_{PEi}} = \frac{\mathrm{CR}(l, q)_{trial1i}}{\mathrm{CR}(l, q)_{trial2i}} \; i \in [1 \cdots 1000] \qquad (5)$$

where *i* represents the bootstrap repetition index. Based on this new population the Efron 95% CI for the $CR(l,\boldsymbol{q})_{PES}/_{PE}$ were obtained.

Catch comparison and catch ratio analyses, by being population independent, are good tools for generalizing the results obtained from comparing the size selectivity of two gears in a given fishery to other fisheries. However, if the aim is to better understand the impacts of that difference in selectivity to the stock where the new gear was tested or catch length pattern obtained by the fishermen, cumulative distribution analysis of the catch weight gives a better understanding and quantification of such impacts. Therefore, cumulative distribution analyses of the catch weight were performed for the catches of each codend used in the three sea trials and the difference between both cumulative distributions within each trial was calculated, henceforth referred to as delta. Cumulative distribution analysis provides the proportion of the total catch up to a given length for the tested gear when fished in that stock population, thus being highly relevant for management purposes. Moreover, the cumulative catch weight distribution analysis is non-parametric and thus independent of any modelling assumptions and is described in this study by:

$$CD\_catch(L) = \frac{\sum_i \{\sum_{l=0}^{l \leq L} [n_{il} \times (a \times l^b)]\}}{\sum_i \{\sum_l n_{il}\}} \qquad (6)$$

where the sum of $i$ is for hauls and $l$ is for length classes, while *a* and *b* are the coefficients from the length-weight equation for Baltic cod. The delta allows quantifying the length dependent difference between the catch weight distributions of the both codends tested in each sea trial, and can be described by:

$$Delta\_CD = CD\_catch(L)_t - CD\_catch(L)_b \qquad (7)$$

where the indices *t* and *b* represent, respectively, the test and baseline codends in each of the three trials. The Efron percentile 95% confidence limits were estimated using a double bootstrap approach. Since, for all three trials both tested codends were fished in parallel and therefore subjected to the same fishing conditions and cod populations, the bootstrapping procedures for each cumulative catch weight distribution curves were performed in the same loop. This approach allows accounting for differences that might have come from variability within the trials.

The evaluation of the different codend's overall performance can also be complemented and summarized using usability indicators. The indicators were adapted from Wienbeck *et al.* (2014) and Santos *et al.* (2016) so that they could be used for catch comparison data instead of cover codend data. Moreover, the indicators were modified to provide the values in weight and not numbers caught to be even more relevant for managers and fishermen. These indicators depend directly on the size structure of the fished population, in contrast to the catch comparison and catch ratio that provide population independent information. Thus, the results are specific to the three trials in this study. However, since the trials were undertaken under commercial conditions and targeting common fishing grounds, the results contain information regarding the usability of the codends in the fishery. Three different codend usability indicators were used:

$$wP_{-} = \frac{\sum_i \{\sum_{l<MCRS} n\mathrm{t}_{il} \times (a \times l^b)\}}{\sum_i \{\sum_{l<MCRS} n\mathrm{b}_{il} \times (a \times l^b)\}} \tag{8}$$

$$wP_{+} = \frac{\sum_i \{\sum_{l \geq MCRS} n\mathrm{t}_{il} \times (a \times l^b)\}}{\sum_i \{\sum_{l \geq MCRS} n\mathrm{b}_{il} \times (a \times l^b)\}} \tag{9}$$

$$dwRatio = 100 \times \frac{\sum_i \{\sum_{l<MCRS} n_{il} \times (a \times l^b)\}}{\sum_i \{\sum_l n_{il} \times (a \times l^b)\}} \tag{10}$$

where the sum of $i$ is for hauls and $l$ is for length classes and *a* and *b* are the coefficients from the length-weight equation for Baltic cod obtained from Danish bottom trawl surveys in the first and fourth quarters of the years 2015 to 2017 in the ICES areas 24 and 25 of the Baltic Sea. $wP_{-}$ and $wP_{+}$ compare the catches weights under and over the MCRS between the test and the baseline codends for each trial. Values of 100 indicate that the test gear catches equally as much as the baseline gear. Therefore, $wP_{-}$ should be as low as possible while $wP_{+}$ should be as high as possible, meaning that no losses ($wP_{+} \approx 1$) or even an increase in the catch above the MCRS ($wP_{+} > 1$) occurred for the test codend in relation to the baseline codend. $dwRatio$ is the ratio between discards and total catch in weight, thus it should be as low as possible, with 0 being the optimal situation where no discards occur.

The CI for the average $nP_{-}$, $nP_{+}$ and $dwRatio$ were estimated using a double bootstrap approach. By using this approach, both within and between haul variations were taken into account. A total of 1000 bootstrap iterations were performed to estimate the Efron percentile 95% confidence limits (Efron, 1982) for all relevant length classes.

## Results

A total of 26 out of 27 hauls were considered valid, with 6 being from the first trial, 10 from the second, and 10 from the third (Table 2). The invalid haul was due to excessive mud in the codend of the test gear. Furthermore, fishing operations were kept as similar as possible to commercial fishing activities, with haul duration, towing speed and fishing depth ranging from 100 to 465 min, 3.1 to 3.4 knots, and 40 to 73 m, respectively. Total catches of cod per haul ranged from 243 to 1763 kg during the three sea trials and all cod caught was length measured. Further details regarding the sea trials are shown in Table 2.

**Table 2.** Summary of the hauls used for the catch comparison analysis of cod. Values within parenthesis are the calculated standard deviations.

| | **Trial 1** | **Trial 2** | **Trial 3** |
|---|---|---|---|
| **No. of hauls** | 6 | 10 | 10 |
| **No. cod caught** | 5 856 | 9 770 | 14 254 |
| **Average cod catch size (kg)** | 1130 (±368) | 782 (±344) | 691 (±159) |
| **Average haul duration (min)** | 317 (±83) | 258 (±66) | 304 (±76) |
| **Average towing speed (knots)** | 3.2 (±0.08) | 3.2 (±0.04) | 3.2 (±0.04) |
| **Average fishing depth (m)** | 54 (±10) | 62 (±11) | 66 (±3) |

Catch comparison analyses were performed on the datasets from each of the three trials. The analysis of model fits did not reveal any issues. The *p*-values and the ratio between residual deviance and degrees of freedom did not indicate any fitting problems for any of the three models (Table 3). Furthermore, plotting the residuals against the length did not show any structure in the residuals from any of the three catch comparison models (plots not shown).

**Table 3.** Fit statistics for the modelled catch comparison rates.

| Trial | *p*-value | Residual Deviance | DOF |
|---|---|---|---|
| **1** | 0.80 | 37.66 | 46 |
| **2** | 0.12 | 62.12 | 50 |
| **3** | 0.11 | 65.74 | 53 |

The results obtained from the first trial are shown in Figure 1. The catch ratio, $CR(l,\boldsymbol{q})$, curve obtained showed that the IND codend caught significantly, although just slightly, more cod between 45 and 48 cm than PES, while no significant difference was found for the remaining length classes. The largest significant difference occurred for the length of 47 cm, where IND caught at least 1.02 times (estimated to be on average 1.20 times) more cod than PES. The cumulative catch weight distribution curves obtained from both codends showed similar catch patterns. However, the $Delta\_CD$ shows that the cumulative catch profiles of IND and PES are significantly different for the lengths between 35 and 40 cm. $Delta\_CD$ shows that the cumulative catch, in weight, for the lengths 35 to 40 cm is lower for IND, with the largest absolute difference occurring at 39 cm, -5.6% (CI from -12.1 to -0.8). This significant difference comes from the cumulative effect of IND catching less cod up to the length of 39 cm, as seen in the $CR(l,\boldsymbol{q})$, despite not been significant in the $CR(l,\boldsymbol{q})$. The usability indicators for cod for the first trial show that IND, when tested against PES, currently being used in the fishery, reduced the catch of cod under the MCRS by 27% (wP-) while increasing the catch of cod above the MCRS (wP+) by 7%. Moreover, IND showed a lower discard ratio ($dwRatio$) than PES, 3.7% (CI from 2.2 to 4.8) and 5.2% (CI from 3.5 to 7.6), respectively.

Despite on average indicating an overall positive performance of IND, wP- and wP+ were not significant since in both cases the CIs included the value of 1.

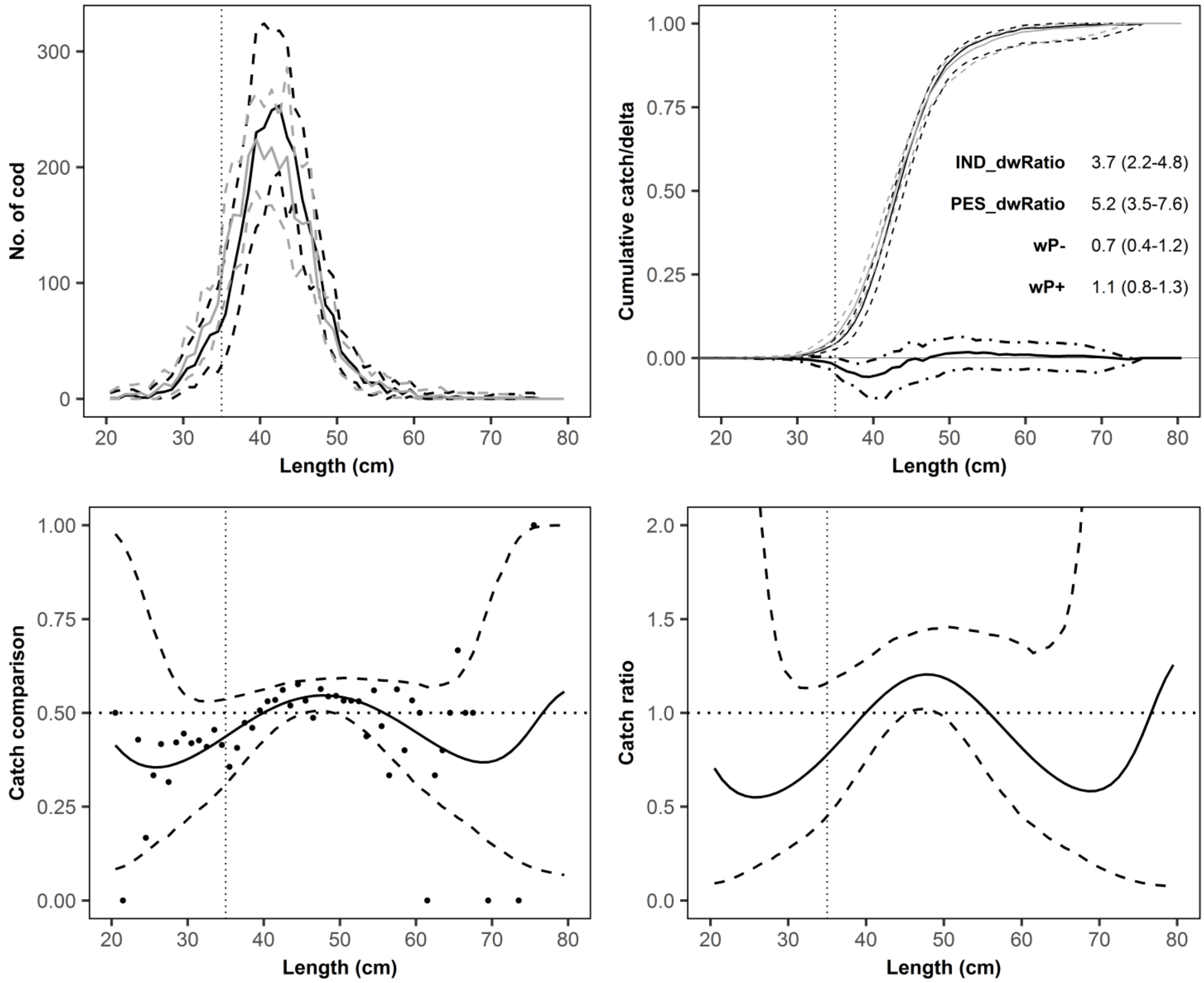


**Figure 1** Results from trial 1. Top-left panel shows the population caught in numbers by IND (black line) and PES (grey line). Top-right panel shows the cumulative catch weight distributions for IND (black thin line) and PES (grey thin line) and respective delta (black thick line). The usability indicators are also shown in the top-right panel. Estimated average catch comparison and catch ratio curves are shown in the bottom-left and bottom-right panels, respectively. Dotted grey horizontal lines represent when both gears are fishing equally efficient. The 95% confidence intervals estimated for all curves in all panels are shown in the respective broken lines. The vertical dotted line shows the minimum conservation reference size of 35 cm for Baltic cod.

In the second trial, where PES was changed to PE, the IND codend caught significantly more cod at the length classes between 26 and 47 cm, while no significant difference was found for the other length classes (Figure 2). At the MCRS, IND caught at least 2 times more cod (on average 4 times more) than PE. Moreover, the cumulative catch distributions curves obtained for IND and PE also show two distinct catch profiles. The $Delta\_CD$ shows that IND caught, in weight, significantly more cod than PE for the lengths between 34 and 53 cm, with the largest delta occurring at 44 cm with a total difference of 17.8% (CI from 10.35 to 25.10). Although $CR(l, \boldsymbol{q})$ showed that IND has relatively higher catch rates of smaller cod, this increase in catch rates starts to impact the cumulative catch profile only at the length of 34 cm. Furthermore, the usability indicators also showed a significantly higher retention of cod under the MCRS, 413%, and a significant increase of cod above the MCRS, although of a lower magnitude, 45%. Although the relative increase in undersized cod being around 9 times higher than the increase of oversized cod, the absolute increase in catch between both codends for both undersized and oversized cod showed opposite results as shown by the $Delta\_CD$ and the absolute catches. Regarding the discard ratio of cod in weight, IND showed values approximately 3.5 times higher than PE, 3.8% (CI from 1.4 to 6.6) and 1.1% (CI from 0.6 to 1.5], respectively, although still being a relatively low discard ratio ($dwRatio$).

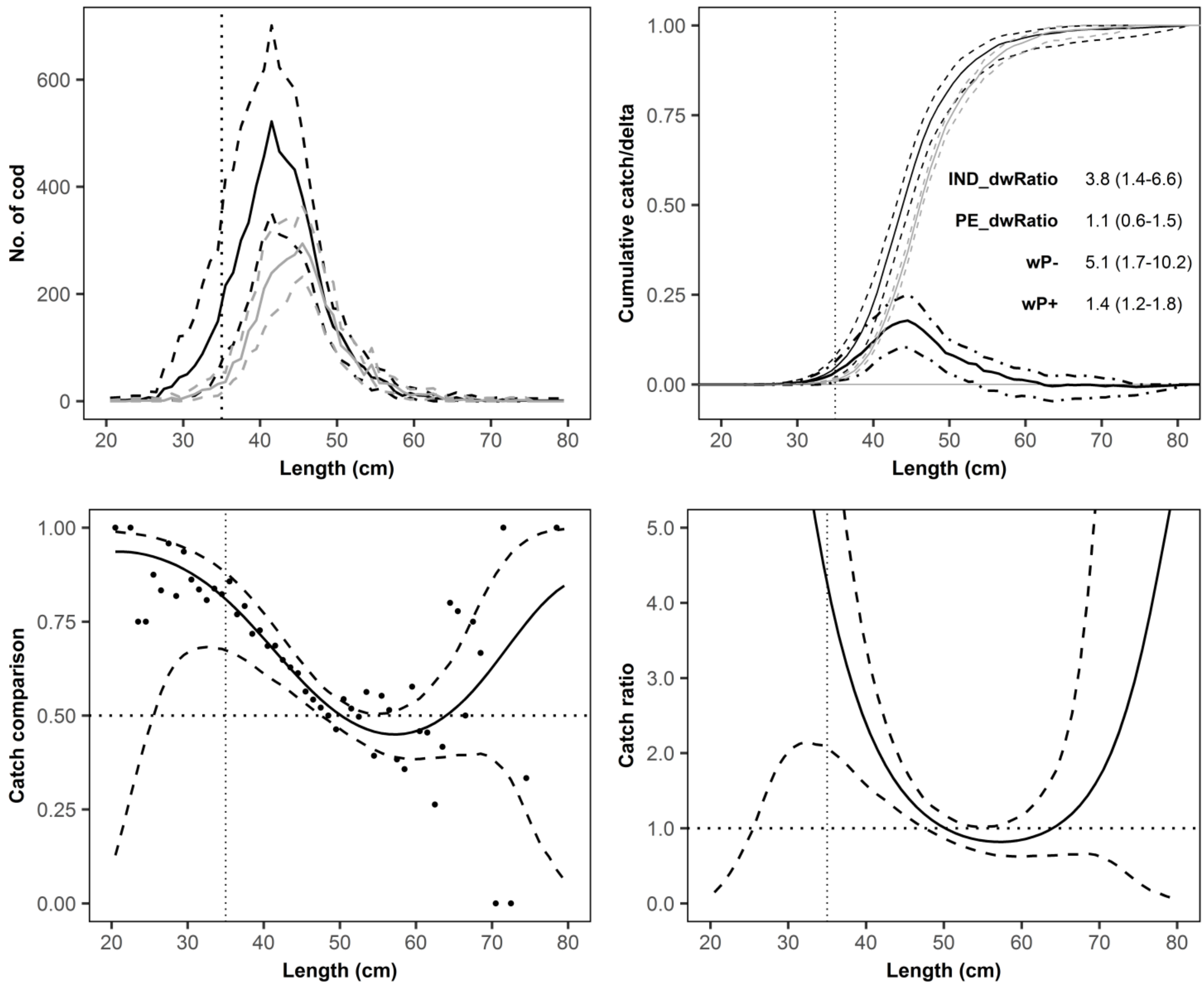


**Figure 2** Results from trial 2. Top-left panel shows the population caught in numbers by IND (black line) and PE (grey line). Top-right panel shows the cumulative catch weight distributions for IND (black thin line) and PE (grey thin line) and respective delta (black thick line). The usability indicators are also shown in the top-right panel. Estimated average catch comparison and catch ratio curves are shown in the bottom-left and bottom-right panels, respectively. Dotted grey horizontal lines represent when both gears are fishing equally efficient. The 95% confidence intervals estimated for all curves in all panels are shown in the respective broken lines. The vertical dotted line shows the minimum conservation reference size of 35 cm for Baltic cod.

The effect of increasing the circumference was tested in the third trial and the results shown in Figure 3. The LC codend caught significantly more cod below 45 cm when compared to the PE codend, while catching significantly less cod between 47 and 60 cm. No significant difference was found for other lengths. The increase in circumference from 50 to 92 open meshes led to a minimum increase of 40% (on average 74%) of the catch of cod at the MCRS. The $Delta\_CD$

obtained from the cumulative catch curves for both codends showed a significant difference in the cumulative catch profile for lengths between 30 and 47 cm. Moreover, the largest delta value occurs at 42 cm with a total difference of 8.2% (CI from4.2 to 12.3). This significant difference between the cumulative catch profiles of both codends, LC and PE, comes from the large increase of catches of undersized cod, affecting the catch profile up to 47 cm. The increase in codend circumference resulted in an increase of 2.2 times of undersized cod and no change in the catches of oversized cod (respectively, wP- and wP+ in Figure 3). Moreover, the LC showed a discard ratio of 3.4% (CI from 2.3 to 4.6) while PE showed a discard ratio of 1.6% (CI from 1.1 to 2.1).

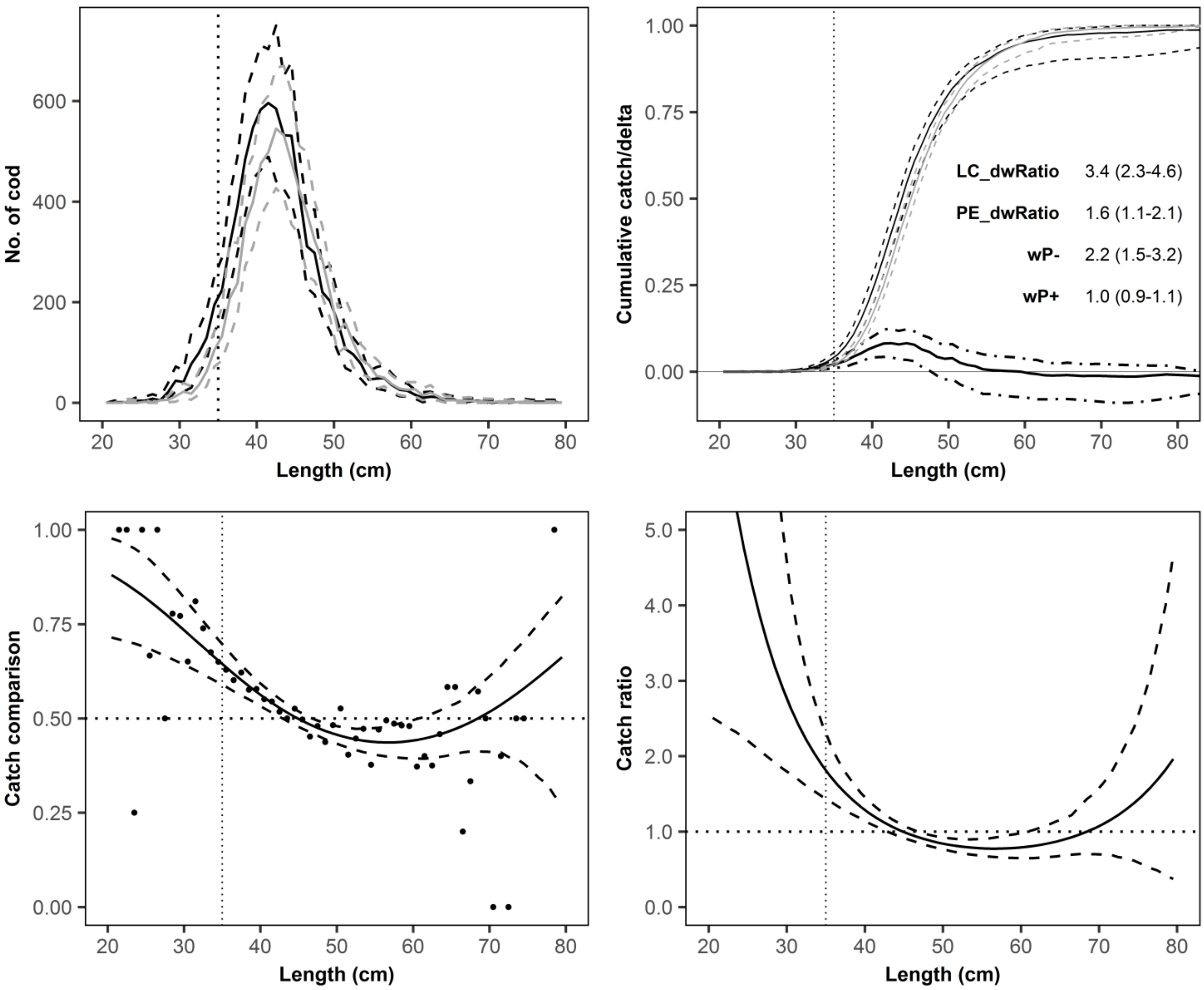


**Figure 3** Results from trial 3. Top-left panel shows the population caught in numbers by LC (black line) and PE (grey line). Top-right panel shows the cumulative catch weight distributions for LC (black thin line) and PE (grey thin line) and respective delta (black thick line). The usability indicators are also shown in the top-right panel. Estimated average catch comparison and catch ratio curves are shown in the bottom-left and bottom-right panels, respectively. Dotted grey horizontal lines represent when both gears are fishing equally efficient. The 95% confidence intervals estimated for all curves in all panels are shown in the respective broken lines. The vertical dotted line shows the minimum conservation reference size of 35 cm for Baltic cod.

Changing the net material from polyethylene (PE) to polyester (PES) significantly increased the catch of cod between 26 and 43 cm, inclusive, while showing no significant differences for the other length classes (Figure 4). At the MCRS, the PES codend caught at least 2.2 times (on average 5 times) more cod than the PE.

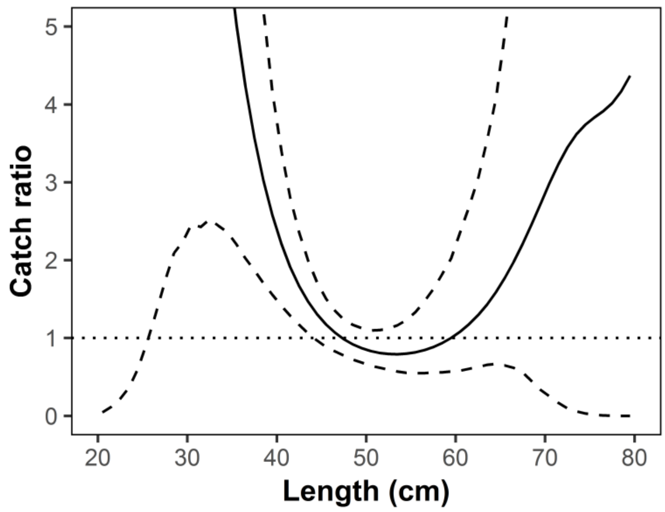


**Figure 4** Estimated catch ratio curve (solid black line) and 95% confidence intervals (broken black lines) for cod obtained when changing the material of the codend from polyethylene to polyester in a T90 120 mm standard codend. Dotted grey horizontal line represents when both codends have equal catch efficiency.

## Discussion

The results from the first and second trials showed that the industry were able to develop a codend, IND, with a size selectivity better suited to the current cod population structure in the Baltic Sea. Moreover, the industry-developed codend showed a better relative size selectivity when compared to the codends presently being used by the Baltic cod trawl fleet. The industry being able to successfully develop gears with more suitable catch profiles than those currently used has been described in previous studies (Catchpole and Gray, 2010). However, the objectives of the fishing industry and scientists are not completely aligned.

While both industry and scientists have the objectives of optimising catch values and reducing discards to increase profit, scientists also need to understand the effect of the single design parameters of a fishing gear. Thus, industry can change several design parameters of a gear to achieve their objectives, as shown in this case study. To understand the individual effects of the different parameters changed in the fishing gear proposed by the industry, three consecutive sea trials were performed in the Baltic Sea. However, due to the complexity of the gear proposed by the industry, it was not possible to experimentally test all four modifications proposed. Therefore, we tested two of these modifications experimentally, material type and codend circumference, and discuss the effect of the two other modifications, mesh size and lastridge ropes, for which effects are better understood.

The results describing the effect of twine material on cod selectivity showed that PES significantly reduced the selectivity for cod when compared to PE. Previous studies reported that for diamond meshes (T0°) twine materials softer than PE, such as PES, increase the codend selectivity (Ferro and O'Neill, 1994; Tokaç *et al.*, 2004). Softer materials allow for an easier escape of individuals when the codend has already some catch build-up. These findings contradict the results obtained in this study, although here diamond meshes turned 90° degrees were used instead of T0°. The objective of turning diamond shaped meshes 90° degrees is to allow the meshes to retain their shape and remain open during the fishing process (Herrmann *et al.*, 2007). A stiffer twine material in a T90° netting will further enhance its effects, as it will help retain the mesh opening angle of the meshes (Herrmann *et al.*, 2009). Opening angles determines how open a mesh is, for example in diamond meshes it can vary throughout the fishing process while for square meshes the angle is stable at 90°. On the other hand, a softer twine material can considerably hamper the effect of T90° netting by reducing the opening angle of the meshes. As our results show, the twine material stiffness in a T0° codend appears to have the opposite effect in a T90°.

The results obtained describing the effect of codend circumference on the relative size selectivity of cod showed that increasing the circumference of the codend from 50 to 92 open meshes significantly increased the proportion of small cod captured. Previous studies presented similar results for cod in the Baltic Sea (Wienbeck *et al.*, 2011; Herrmann *et al.*, 2015), North Sea (Reeves *et al.*, 1992) and based on simulations (Herrmann *et al.*, 2007). The optimal opening angle of the meshes in codends with smaller circumferences is typically reached earlier in the fishing process, and thus facilitating the escapement of smaller cod (Herrmann *et al*., 2007).

The effects of reducing mesh size and adding lastridge ropes were not tested in this study. The effect of reducing mesh size on cod selectivity is well known and documented, where a reduction in mesh size reduces selectivity (e.g. Herrmann *et al.*, 2009; Wienbeck *et al.*, 2011; Wienbeck *et al.*, 2014). While being less well documented, the objective of lastridge ropes is to maintain a high opening angle of the meshes in the codend throughout the fishing process, therefore increasing selectivity (Hickey *et al.*, 1993; Lök *et al.*, 1997).

This case study shows that the industry can, in the terms of overall size selectivity, develop a gear to suit their needs and those of management. This approach also provides them with a more active role in the process, where they are able to develop and test multiple solutions in parallel which are tailored to their specific fisheries. Moreover, the experimental design applied in this study, where the new gear was tested directly against a baseline using the catch comparison method, is particularly well-suited for industry-led gear development trials as it does not interfere with the commercial fishing operation. Furthermore, developing gears in such a manner introduces a proper iterative development and testing phase under commercial fishing conditions, something which has, in general, been lacking in traditional gear development initiatives. Undertaking the development and testing in such a manner can potentially lead to a faster implementation and uptake of gears in the fisheries. However, the speed in the process of introducing new fishing gears can be reduced by the industry putting forward overly complicated gears requiring a complex and costly documentation process.

As seen in this case study, the industry put forward a gear design where multiple design parameters were modified. A total of four modifications were made, where one was found to have opposite effects to what the industry had anticipated (codend circumference) and another perceived not to influence the selectivity (material type). The effects of these parameters would not have been disclosed if the selectivity of the industry-developed gear had only been compared to the baseline. Not dissociating the effects of the different modifications can potentially result in unfavourable modifications being introduced into legislation. For this reason, after the trial the results were discussed with the fishermen involved and the chairman of the local fishermen's organization. Here it was agreed that similar results could most likely have been obtained through a simple reduction in mesh size. This conclusion supports the industry's claim that the currently legislated gears are too selective with respect to the size structure of the Baltic cod population. As a result of this process, the simple reduction of mesh size was presented to fisheries managers and taken forward to evaluation by STECF. Moreover, the scientific testing and documenting of such overly complicated gear designs becomes more expensive and time consuming, more difficult to understand, as well as resulting in an over complication of the gear specifications in legislation and difficulties in enforcement. This can potentially reduce the benefits of industry-led gear development.

Having the industry as the main driver in the development of new fishing gears can facilitate the development of a larger number and more specialized technical solutions. Moreover, it can reduce the time outlay associated with gear development, and increase the acceptance of the new gear by the industry. However, there needs to be an early and continuous involvement from scientists in the development process to advise on expected effects of modifying different design parameters. This early involvement ensures that unnecessary and adverse modifications are not made to the gear, thus facilitating the scientific testing and documentation process for possible implementation in legislation. Furthermore, by understanding the effect of each modification, the response time to new issues in a fishery can be greatly reduced by knowing exactly which gear modifications should be further improved or removed.

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# Paper 3

# Understanding the hydrodynamics of a size sorting grid in a crustacean fishery

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## Abstract

A size-sorting grid with a small bar spacing of 6 mm was proposed to be used in a brown shrimp (*Crangon crangon*) beam trawl fishery. Considering the bar spacing, concerns regarding the hydrodynamics of such grid were raised. Here we experimentally investigated in a wind tunnel the hydrodynamics of four grids with different bar shapes and aimed to identify which parameters affect the hydrodynamics. By observing the similarity criteria according to Reynolds it is ensured that the measurement results are applicable to the grid in water. The four grids were tested at different angles and wind velocities. Porosity and the inclination of the grid were found to be the main parameters affecting the flow in front and behind the grid. The shape of the bars was also found to affect the flow, although to a lesser extent than porosity and angle. This shows that if grids are designed and mounted incorrectly their hydrodynamics performance may be reduced, thus potentially affecting the selectivity performance of the grid.

**Keywords**

Sorting grid, hydrodynamics, wind tunnel, shrimp fisheries

## Introduction

In crustacean trawl fisheries, grids are one of the most common and successful selective devices used globally to reduce unwanted catch (Eayrs 2007; Catchpole and Revill 2008; Lövgren et al. 2016). Traditionally, grids consist of a physical barrier of vertical or horizontal bars, with a given bar shape and spacing used to direct individuals that did not pass through the bars to be released or to an alternative codend (e.g. Isaksen et al. 1992; Eayrs 2007). The use of grids has typically been to reduce the capture of two types of unwanted catch. First, they can be used as a by-catch reduction device, where the bar spacing will be set to physically allow individuals within the size range of the target species to pass through the grid and enter the codend, while larger non-target species, unable of passing through the grid, escape through an opening (Grimaldo and Larsen 2005; Kvalsvik et al. 2006; Eayrs 2007). Secondly, grids can be used as size sorting devices, where the smallest individuals of the target species are able to escape before they reach the codend (Kvalsvik et al. 2002; Larsen et al. 2016; 2018). Usually, this size sorting requires the use of a smaller space between the grid's bars, particularly if the target species is small, e.g. shrimps.

The brown shrimp (*Crangon crangon* Linnaeus, 1758) beam trawl fishery is an important fishery in the North Sea with an international fleet of approximately 550 beam-trawl vessels, mainly from the Netherlands, Germany and Denmark. In the recent years, it generated total annual landings of around 30 000 tonnes (ICES 2016). The fishery is certified by the Marine Stewardship Council (MSC), and as part of the MSC requirements to maintain the certification, the fishery has to increase the minimum mesh size (diamond mesh) from 22 mm in 2016 to 26 mm in 2020 (MSC 2017). Concerned that the increase in mesh size would result in a substantial loss of marketable size brown shrimp, the Danish fishermen proposed the introduction of a size sorting grid with a bar spacing of 6 mm as a possible alternative to the 26 mm diamond mesh codend.

The use of a grid with a bar spacing of 6 mm raised the question of how such grid affect the water flow since water flow issues have previously been reported for other grids with larger bar spacings, e.g. 19 mm (Grimaldo and Larsen 2005; Grimaldo 2006). The sorting effectiveness of fishing grids has been hypothesised to be highly influenced by the flow of water passing through and the flow that is deflected by the grid (Riedel and DeAlteris 1995). If the area coefficient, i.e. the ratio between solid and total area, of the grid face is too low, the decrease in water flow in front of the grid can be substantial (Grimaldo and Larsen 2005; Grimaldo 2006), therefore affecting negatively the sorting capacity of the grid (Grimaldo et al. 2015; Sistiaga et al. 2016). In the case of brown shrimp, a species with relatively little swimming capacity (Arnott et al. 1998), the water flow that goes through the grid and that is deflected by it is of even greater importance (Valdemarsen 1989). A too high water flow through the grid may result in a loss of commercial sized individuals due to them being pushed through the bars, while if the velocity is too low, a relatively large portion of catch may not contact the grid, thus decreasing the effectiveness of the grid (He and Balzano 2012). Therefore, understanding the parameters that affect the hydrodynamics of a grid, and in particular the flow through it, is highly relevant when designing a sorting grid, especially in crustacean fisheries like the brown shrimp fishery where the proposed bar spacing is very small.

In addition to the bar spacing and area coefficient, other factors are known to influence the grid hydrodynamics. The inclination angle of the grid in relation to the towing direction has been shown to affect the water flow through the grid (Riedel and DeAlteris 1995; Maurstad 1997), although showing contradictory results. Riedel and DeAlteris (1995) suggest that at lower angles less flow is lost when passing through the grid bars, while Maurstad (1997) suggest the opposite. The shape of the bars is also known to influence the hydrodynamics of a grid, although it has been suggested that the influence of this factor is of less importance than the previous factors (Riedel and DeAlteris 1995; Grimaldo 2006). Despite the hydrodynamics of grids being identified as an important aspect for their success in fisheries (e.g. Kvalsvik et al. 2002; Grimaldo and Larsen 2005; Kvalsvik et al. 2006; He and Balzano 2012; Larsen et al. 2016; Larsen et al. 2018), only one study, Riedel and

DeAlteris (1995), has tried to identify and quantify in a systematic way what parameters affect the hydrodynamics of grids. In Riedel and DeAlteris (1995), a species selective grid with a bar spacing of 19 mm was tested, a bar spacing 3 times larger than the size selective grid proposed for the brown shrimp fishery (6 mm). Thus, there is the need to better understand the hydrodynamics around size selective grids that typically have smaller bar spacing.

Several grids have been developed and tested by both industry and scientists, however, measurements of the hydrodynamics in the system are often lacking. Therefore, this approach could be characterized as a trial and error approach (Graham 2010). This type of approach can be quite costly, both in terms of time and money. Hence, the aim of this study was to understand the effect of different parameters on the hydrodynamics of grids through the use of a systematic experimental design in a wind tunnel. The parameters tested were grid porosity, angle, shape of grid's bars, and approaching flow velocity. Wind tunnels have been previously used to successfully describe the hydrodynamics of other towed fishing gears (Reite and Sørensen 2006; Paschen et al. 2008; Mellibovsky et al. 2015; 2018).

## Material and Methods

Four grids with different bar cross section were tested. The overall dimensions of the grids, the cross section shapes and the averaged grid bar dimensions are depicted in Fig. 1. Throughout this study, the different grids tested are referred to based on the cross sectional shape of their bars. The grid with a cylindrical cross section is referred to as "Cylindrical", the two grids with drop shaped bars are referred to as "Drop 4" and "Drop 8", and the grid with rectangular bars with rounded corners is referred to as "Rectangular". The drop shaped geometries consist of a circular front part with a fin of triangular shape attached. The grid bars have been manufactured from glass-fibre reinforced plastic.

The porosity $\beta$ of the grids, the ratio of the open area to the total area, is calculated according to

$$\beta = \frac{bs}{w + bs} \tag{1}$$

where $w$ denotes the width of the bar and $bs$ the bar spacing. With a bar spacing of 6 mm the porosities are: Cylindrical 0.43, Drop 8 0.43, Drop 4 0.60 and rectangular 0.61.

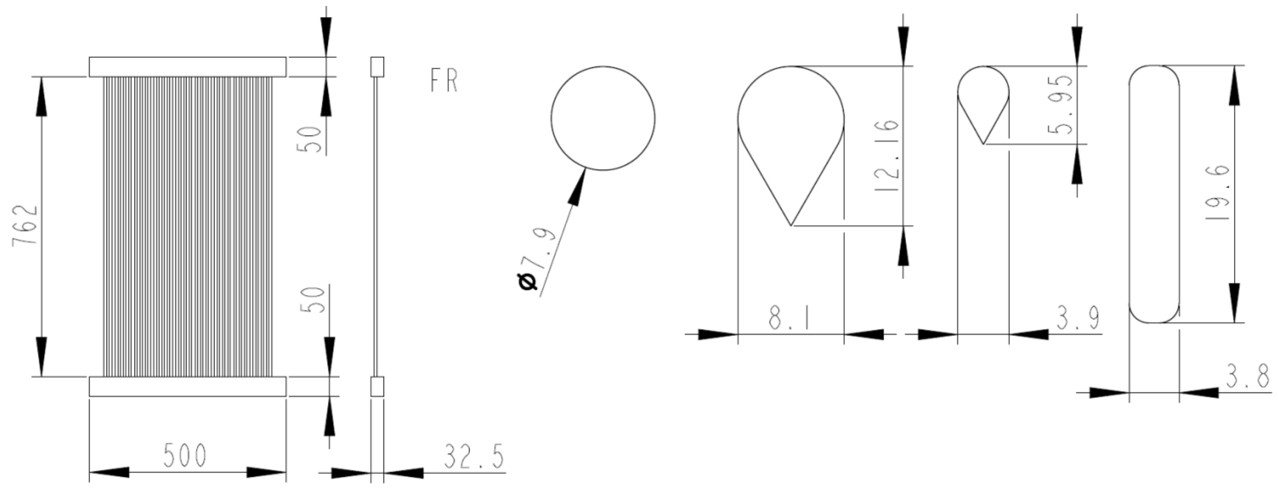


**Figure 1.** Technical sketch of grid and grid bar dimensions (in millimetres).

The experimental investigations have been carried out in the large subsonic wind tunnel belonging to the chair of ocean engineering, University of Rostock. It is a return-circuit wind tunnel (Göttingen type) with an open test section of 2.8 m length. The side length of the square nozzle outlet is 1.4 m. The wind velocity is determined by a differential static pressure measurement at the inlet and outlet of the nozzle. The pressure is measured with a differential pressure transducer (Baratron 220DD from MKS Instruments, Inc.) with a measurement range of 20 Torr, i.e. 2,666 Pa. To determine the air density, the ambient barometric pressure (transducer model 3.1157.10.161 from Adolf Thies GmbH & Co. KG), the temperature and humidity (model 6605 probe and transducer unit model 6651 from testo AG) are measured. With the measurement technique used, the wind velocity can be determined with a relative uncertainty of 2 %.

By choosing proper conditions in the wind tunnel the flow patterns and loads on the grids are comparable to conditions in water. These conditions are achieved if geometric, kinematic and dynamic similarities are met. Geometric similarity exists when the wind tunnel model and full-scale objects are similar in shape. Since the grids were tested in full-scale, geometric similarity was achieved. Kinematic similarity means that for time dependent motions the ratios of corresponding time intervals are constant, i.e., the streamlines are similar. There is kinematic similarity if the flow velocities are comparable, taking into account the fluid properties. Dynamic similarity exists when the ratios of forces acting on the model and the grid are the same. For the grids, assuming a steady flow, the ratio of the convective inertia forces and the viscous forces are constitutive for the flow patterns. Thus, dynamic similarity is achieved by keeping the ratio of the convective inertia forces to the viscous forces - which is expressed by the Reynolds number - constant:

(2) $$Re = \frac{u \cdot L}{\nu} = const. \Rightarrow \; Re_{model} = Re_{full-scale}$$

where $L$ is a characteristic length (here: width of the gird bar), $u$ a characteristic velocity and $\nu$ the kinematic viscosity of the fluid. For the wind tunnel velocity, or approach velocity, $u_0$ it follows:

(3) $$u_0 = u_{water} \cdot \frac{\nu_{air}}{\nu_{water}}$$

In the brown shrimp beam trawl fishery, trawls are typically towed at between 3 to 3.5 kn. To allow for variation in the towing velocity, 2, 3 and 4 kn velocities were investigated. With $\nu_{air} = 14.6 \cdot 10^{-6}$ m$^2$/s and $\nu_{water} = 1.36 \cdot 10^{-6}$ m$^2$/s the approach velocities in the wind tunnel are calculated as approximately 11.5, 17.3 and 23.1 m/s. Further reading concerning similarity criteria may be found in Fridman (1986) or Ward and Ferro (1993).

*Measurement technique used, experimental set up*

The grids were attached to a steal construction that allowed the grid to be rotated 360° via a turntable. Fig. 2 provides a general overview of the setup in the wind tunnel. In Fig. 3, the defined coordinate systems are depicted. The $x$-axis of the global right-handed coordinate system aligns with the direction of the undisturbed flow in the wind tunnel. The $z$-axis points to the bottom of the test section. The $y$-axis points towards the reader. The $x$- and $z$-axes lie in the symmetry plane of the grid. For measurements in front of the grid, the origins of the coordinate systems lie in the plane spanned by the leading edges of the grid bars, while for measurements behind the grid, the origins lie in the plane spanned by the trailing edge of the grid bars. The local grid fixed coordinate system has an axis normal $n$ to the grid plane, a tangential axis $t$ along the grid bar and a tangential axis aligned with the $y$-axis but of opposite direction. The grids inclination angle is the angle between the direction of the undisturbed flow and the grid surface plane, denoted by $\alpha$ in Fig. 3. Grid angles of 90°, 60°, 45° and 30° were investigated.

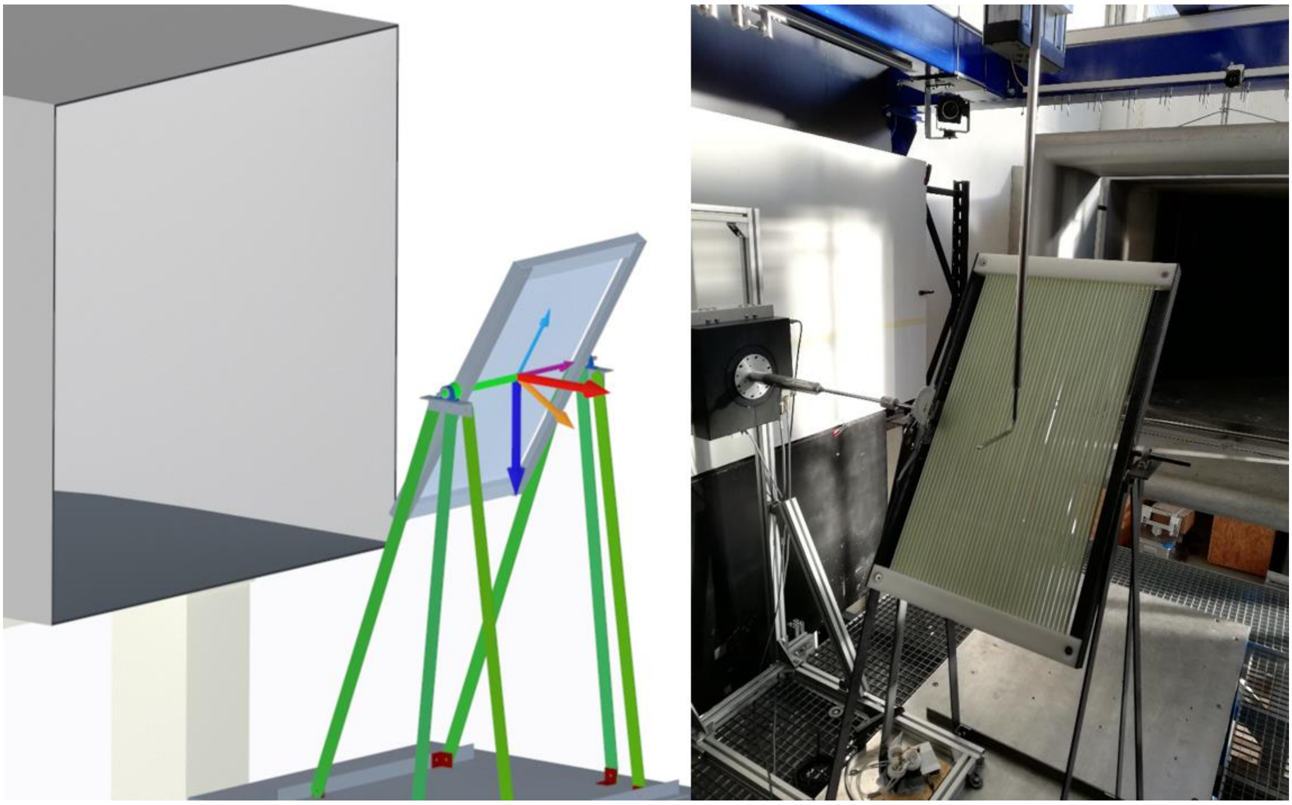

**Figure 2.** Schematic view of the grid in the test section (left panel). Test arrangement in the wind tunnel's test section (right panel).

To measure the static pressure in front of and behind the grid, the static pressure ports of two Prandtl tubes, which were aligned to the flow, were used. In Fig. 3, the measurement positions are indicated by black crosses. The closest measurement point to the front of the grid was 110 mm, and 85 mm to the back of the grid. A total of 48 pressure measurements were taken for every angle of attack and every investigated speed. 24 measurements with a $y$-position in line with a grid bar and 24 at $y$-position between the grid bars.

For measuring static pressures below 100 Pa, a MKS Baratron 120AD pressure transducer (100 Pa measurement range, accuracy +-0.12% of reading) from MKS instruments Inc. was used. Pressures exceeding 100 Pa were measured with a MKS Baratron 220DD pressure transducer (10 kPa measurement range, accuracy +-0.15% of reading).

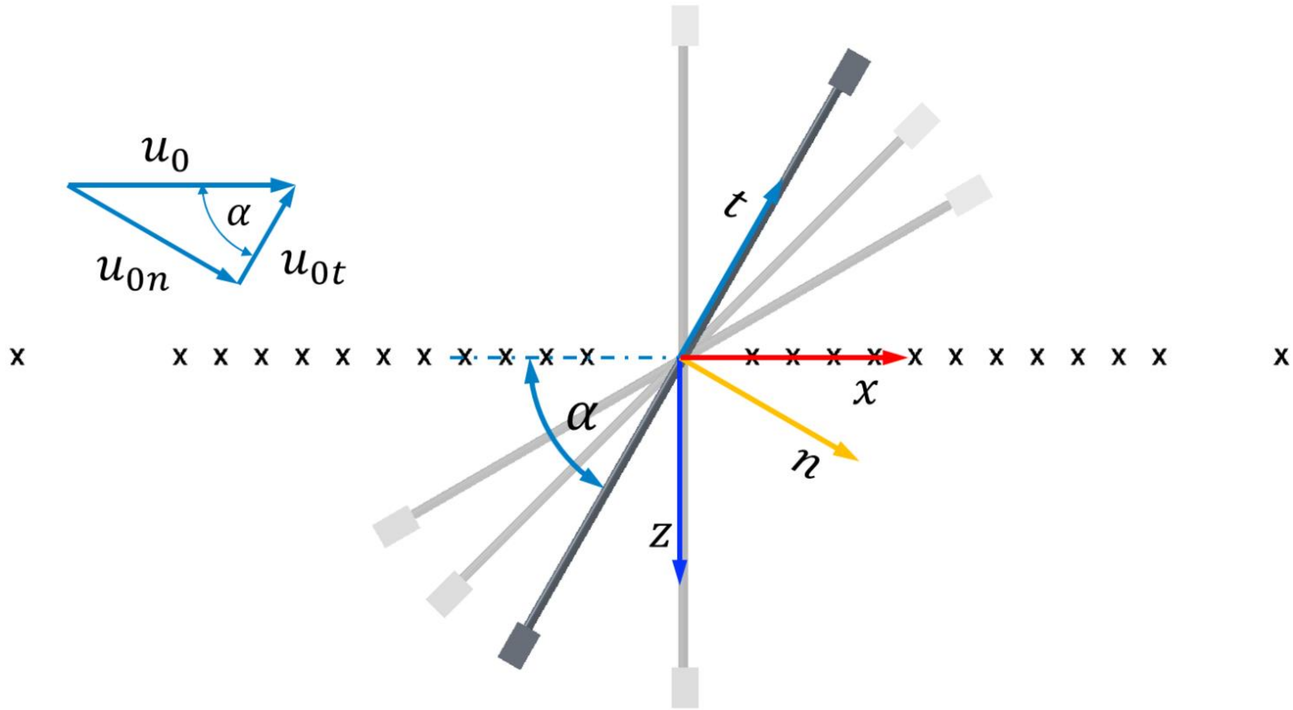


**Figure 3.** Side-view of the grid in the $\boldsymbol{x}$-$\boldsymbol{z}$-symmetry plane and the coordinate systems chosen. The black crosses indicate the positions of the static pressure measurements.

Velocity measurements were conducted with a constant-temperature-anemometer (CTA) system of the type Multichannel CTA 54N81 from Dantec Dynamics AS (www.dantecdynamics.com). Two dual sensor-hot-wire probes, type 55P63 and 55P64, were used to record the velocity in front of and behind the grid. The velocity data were temperature corrected using the temperature probe 90P10.

The dual-sensor probes were oriented to obtain velocity information in the $x$- and $z$-direction. Flow components in the $y$-direction will bias the reading, therefore measurement positions were chosen in or close to the grids $x$- $z$-symmetry plane and not at locations where the proximity of the grid affected the $y$-direction of the flow. From the velocity readings, the flow magnitude was calculated according to:

$$|u| = \sqrt{u_x^2 + u_y^2 + u_z^2} \quad (4)$$

with $u_y$ being expected to be zero due to how the grid is positioned in relation to the direction of the approaching velocity. In Fig. 6, the measurement positions are indicated by the starting point of the vectors showing the flow direction. The normal distance between measurement positions and the front of the grid was at the closest point 18 mm. Due to a failure of the front probe, the measurement program had to be adjusted by using the back probe as front probe as well. As a result, the normal distance closest to the grid was 35 mm for the investigations of Drop 8 and Cylindrical. Furthermore, only the measurement points with a coordinate $t \geq 0$ could be measured. The horizontal distance between the back of the grid and the closest measurement point was 85 mm. A total of 82 CTA measurements were recorded for the Drop 4 and Rectangular grids, and 57 for the Drop 8 and Cylindrical grids in each $x$-$z$-measurement plane for four different grid inclination angles and the approaching velocities of 11.5, 17.3 and 23.1 m/s.

*Flow through grids*

A grid affects the flow in a same manner as described by Laws and Livesey (1978) for gauze screens or by Blendermann (1987) for nettings and cables. It is a resistance $R$ to the flow, which may be expressed by

$$R = \Delta p \cdot A_{grid} \quad (5)$$

where $\Delta p$ is the pressure loss of the flow across the grid and $A_{grid}$ denotes the grids frontal area. When the grid is inclined to the flow, the flow is deflected to the normal plane of the grid.

Assuming a steady inviscid and irrotational flow, and a normally oriented grid, the Rankine-Froude model (or actuator disc model, e.g. chapter 5 in Gasch and Twele (2011)) and the Bernoulli equation may be adapted to allow for a general understanding of the flow properties in front of and behind the grid.

Following the flow along a streamline to the grid, the relation between pressure and velocity in front of the grid can be expressed by the Bernoulli equation (neglecting the gravity term because the height level is equal),

$$\frac{\rho}{2} \cdot u_0^2 + p_0 = \frac{\rho}{2} \cdot u_1^2 + p_1 = constant \tag{6}$$

where the index 0 indicates the streamline position far in front of the grid, index 1 indicates the position in close proximity to the grid, and $\rho$ indicates the density of the fluid.

In the case of a stagnation point on a grid bar, the velocity $u_1$ is zero and it follows that

$$\frac{\rho}{2} \cdot u_0^2 + p_0 = p_1, \qquad \frac{p_1 - p_0}{\frac{\rho}{2} \cdot u_0^2} = 1. \tag{7}$$

The static pressure coefficient is defined as

$$c_p = \frac{p_x - p_0}{\frac{\rho}{2} \cdot u_0^2} \tag{8}$$

where $p_x$ denotes the static pressure at location $x$. Thus, a $c_p = 1$ implies that the flow in front of the grid came to rest. A $c_p$ value between 0 and 1 indicates a decreased flow velocity in comparison to the reference. In the experiments, the wind tunnel velocity $u_0$ and the ambient static pressure $p_0$ at the nozzle outlet were used as references.

Following the approach of the Rankine-Froude model, the grid is assumed to be of infinitesimally small depth and the grid is represented only by a pressure loss. Thus, the flow is uniform and one-dimensional behind the grid, and the Bernoulli equation for a streamline starting right behind the grid to a distance downstream may be written as

$$p_2 + \frac{\rho}{2} \cdot u_2^2 = p_0 + \frac{\rho}{2} \cdot u_3^2 \tag{9}$$

where the index 2 indicates the streamline position right behind the grid and index 3 indicates the position further downstream where the ambient pressure $p_0$ is existent again. Since the grid is assumed to be of infinitesimally small depth, the position right in front of and just behind the grid are in one location. Further, mass conservation demands $u_1 = u_2$ and by subtracting Eq. 9 from Eq. 6 it follows

$$(p_1 - p_2) = \Delta p = \frac{\rho}{2} \cdot (u_0^2 - u_3^2) \tag{10}$$

Since the grid is a resistance to the flow, the pressure loss $\Delta p$ across the grid is larger than zero and hence the velocity behind the grid is smaller than the approaching flow $u_o$. The velocity at the grid is deduced by equating Eq. 5, with the expression for the resistance $R$ being derived by the balance of axial momentum far up- and downstream of the grid

$$R = \rho \cdot u_2 \cdot A_{grid} \cdot (u_0 - u_3). \tag{11}$$

Thus, the velocity is given by

$$u_1 = u_2 = \frac{1}{2} \cdot (u_0 + u_3). \tag{12}$$

Since the flow velocity $u_3$ further downstream of the grid is smaller than the approach velocity $u_0$, the velocity at the location of the grid will also be smaller. Inserting Eq. 12 in Eq. 6 and Eq. 9 and solving for the pressure $p_1$ and $p_2$, the flow properties in front of and behind the grid are described.

$$\begin{gathered} p_1 = p_0 + \frac{\rho}{2} \cdot (u_0^2 - u_1^2) \\ p_2 = p_0 - \frac{\rho}{4} \cdot (u_0^2 + u_0 \cdot u_3 - u_3^2) \end{gathered} \tag{13}$$

Based on the above presented theory, it is expected that the flow approaching the grid is decelerated and the static pressure is increased above the ambient pressure level. Across the grid, a pressure drop occurs, and the pressure right behind the grid is below the ambient pressure $p_0$ at a velocity smaller than the approach velocity. With increasing distance to the grid, the static pressure recovers to the level of the ambient again, resulting in a further velocity decrease. Since the static pressure behind the grid is below the ambient, the pressure loss coefficient $c_p$ will be negative and will approach zero at a distance downstream.

The Rankine-Froude model is suitable to give a general understanding of the flow patterns and, as can be seen above, the pressure loss across the grid is a major property affecting the flow. However, the pressure loss is substitutional for the acting resistance components. To understand the effect of different grid bar geometries, the assumption of an inviscid flow is not valid and a closer look on the resistance components is necessary. For the flow through and around the grid, two components are of major importance. First, the resistance due to surface friction and second, the form resistance which is occurring when the flow around the grid's components does not follow the components contour. The flow separates from the surface and forms a wake region where eddies are generated which drain energy and reducing the pressure at the downstream side. Integrating the pressure distribution over the surface yields to the form resistance. Thus, under the same flow conditions, a larger wake region implies a larger form resistance.

The flow through a grid is governed by its porosity (see Eq. 1). From the mass flow conservation, it follows

$$u_{n\ grid} = \frac{u_{1n}}{\beta} = \frac{u_{2n}}{\beta} \quad (14)$$

where $u_{n\ grid}$ denotes the average normal velocity in between the grid's bars. The components of the flow approaching and leaving the grid normally are denoted by $u_{1n}$ and $u_{2n}$, respectively. Since the form resistance as well as the frictional resistance are dependent on the flow velocity, it is expected that grids with low porosities have a higher resistance as the velocity in between the grid's bars is higher.

To be able to link the grid's hydrodynamics and its potential sorting capability, the tangential and normal flow components were calculated from the CTA datasets. The flow that passes normally through the grid is denoted by $u_n$ and is the flow which transports undersized catch through the grid. The upwards flow along the grid surface, the tangential flow, is denoted by $u_t$ and is the flow which transports catch along the grid. Only the measurement points closest to the grid surface have been evaluated. To allow for comparison of the datasets, the tangential and normal flow components have been normalized to the decomposed approaching flow $u_0$ (Fig. 3). Thus

$$u_N = \frac{u_n}{u_{n0}} = \frac{u_n}{u_0 \cdot \sin\alpha}$$
$$u_T = \frac{u_t}{u_{t0}} = \frac{u_t}{u_0 \cdot \cos\alpha} \tag{15}$$

where $u_N$ and $u_T$ denote the relative velocities.

## Results

A total of 2304 static pressure measurement points were obtained considering the different combinations of bar shape, grid angle and approaching velocity, while a total of 3336 velocity measurements from the CTA system were obtained. The reading of the wind tunnel velocity for the CTA measurement behind the Drop 8 grid, at an approaching flow of 3 knots equivalent and 60° angle of attack was considered invalid after analysing the data and was therefore removed from the analysis.

The two static pressure datasets, one in line with the central bar of the grid and the other in line with the adjacent space between the bars, were obtained for all different combinations of grid angles, bar shapes and approaching velocities. The static pressure coefficient (Eq. 8) is used to present the pressure data and is plotted in Fig. 4 and 5 in relation to $x$, the distance in front of and behind the grid. In Fig. 4 A and B, given here as an example of the complete dataset, the results for all four bar shapes at an angle of 60° are shown. Inspecting the run of the curves it becomes apparent that the general characteristic is congruent with the expectation from the Rankine-Froude model presented above. In front of the grid, the static pressure increases, across the grid a pressure drop occurs, and behind the grid the static pressure recovers to the ambient level. On closer examination of Fig. 4, it can be noted that the overall pattern and quantity of the static pressure coefficient is almost independent of the approach velocity. A slight effect of the approach velocity can be seen for the static pressure values only behind the Drop 8 grid (Fig. 4A), where higher approach velocities showed slightly lower pressure values. This slight effect of the approach velocity was also present for the Drop 8 grid at an angle of 90° (see figures in supplementary material), whereas for the same grid no effect was observed for the 30° and 45° angles (see figures in supplementary material). For the other three bar shapes, regardless of the grid angle, no effect of the approaching flow velocity was observed (see figures in supplementary material). Furthermore, no difference between the measurement points taken in line with the bar or between bars was observed for any bar shapes, angles and approaching velocities, as seen in Fig. 4, where the solid and dashed lines overlap. It is expected that local flow interferences due to the grid are subsided at the distance of the measurement position closest to the grid.

Due to these negligible differences between approach velocities, in the range of the investigated velocities, and relative position of the measurements, all subsequent results shown in this study will consider only the results for the approaching velocities equivalent to the towing speed of 3 knots (wind velocity of 17.3 m/s) and measured aligned with the central bar of each grid. The entire static pressure measurements are given in the supplementary material (Fig. S1, S2 and S3).

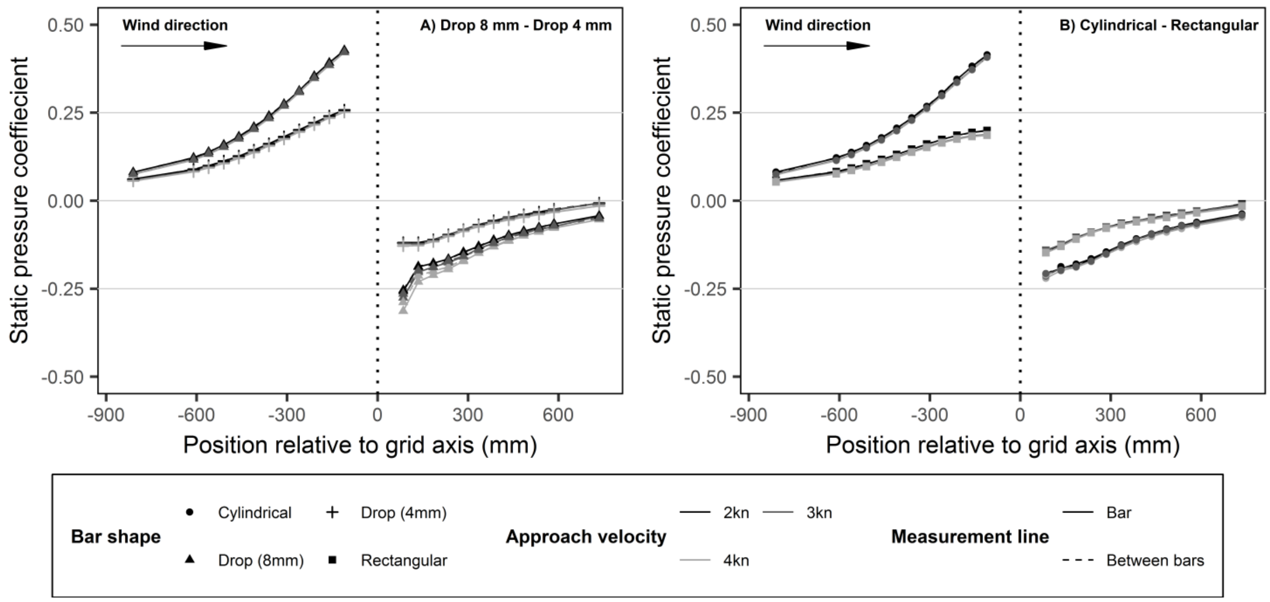


**Figure 4.** Static pressure coefficient $c_p$ at different distances in front (x<0) and behind (x>0) the grid surface (x=0, marked by the vertical dotted line). Grid angle 60°.

In Fig. 5, a comparison of the static pressure measurements of the grids inclined at the different angles is presented. Overall, it can be noted that the static pressure coefficient data are grouped pairwise dependent on the porosity. It can be noted that the increase of the static pressure coefficient $c_p$ in front of the grid is larger for the Drop 8 and Cylindrical grids than for the grids with higher porosity, at all investigated grid angles. Furthermore, the values for $c_p$ behind the grid are lower for the grids with lower porosity, which implies that the pressure loss across the grids, and hence the resistance of the grids with lower porosity, is larger than for the grids with the higher porosity. Inspecting the run of the curves of the Drop 8 and Cylindrical grids, it becomes apparent that there is no distinctive difference between them. Contrary, a difference of the grids with similar high porosity, Drop 4 and Rectangular, is visible. The grid with the rectangular shaped bars induces the least increase of $c_p$ in front of the grid, whereas behind the grid the run of the $c_p$-curve is nearly congruent/very similar to the run of the curve of the Drop 4 grid.

An effect of the top and bottom members of the grid frame was observed for the two lower grid angles, 30° and 45° (Fig. 5A and B). Since the flow has to pass around the frame it is locally accelerated, which results in a decrease of the static pressure, indicated by a dent in the run of the

$c_p$-curve. At lower angles, the distance between frame bars and the location of measurement is reduced and hence the effect is more distinct at lower angles. In addition, this effect is more pronounced in front of the grids with higher porosity since the flow in front of these grids is not as decelerated, resulting in higher velocities.

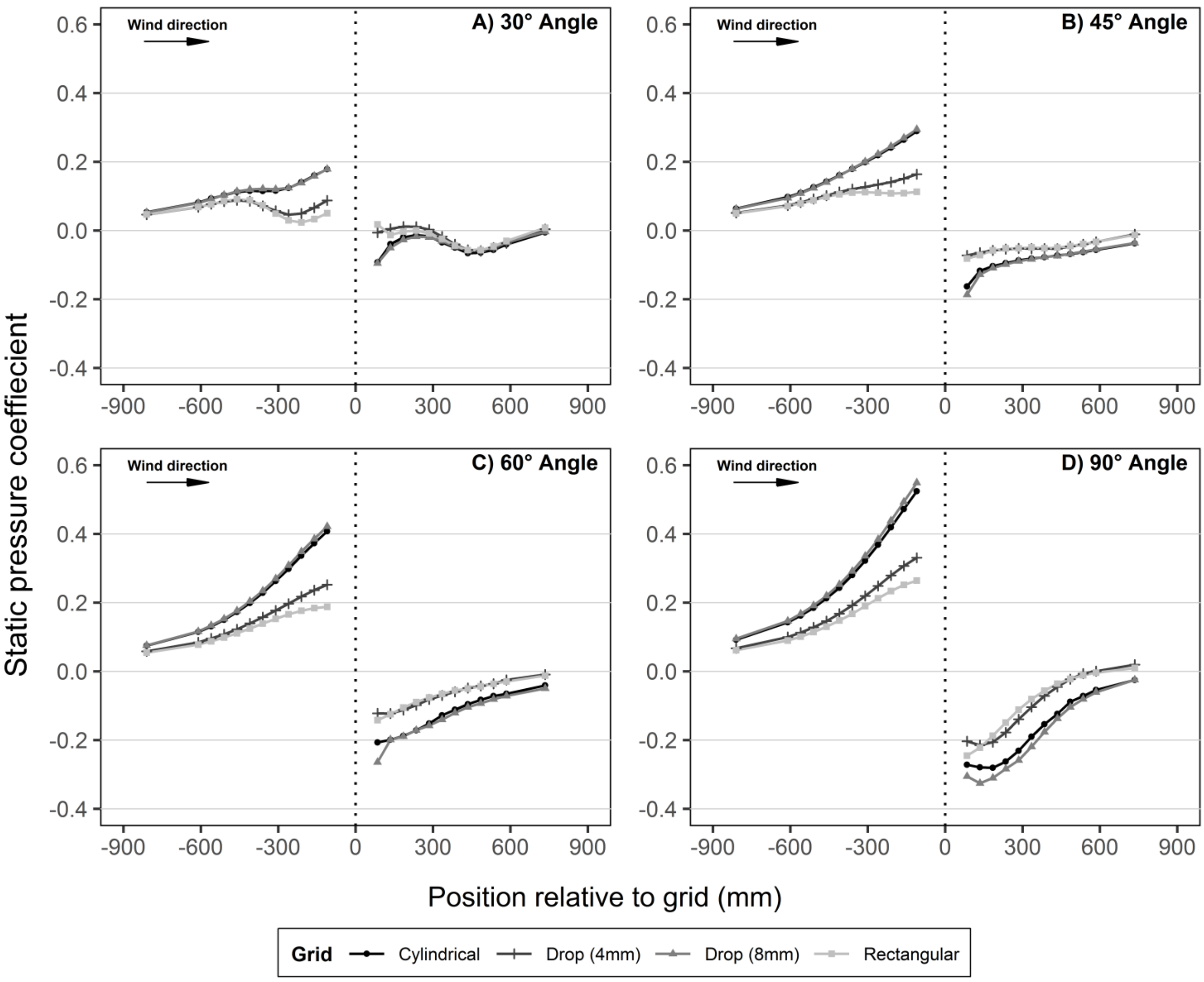


**Figure 5.** Static pressure coefficient at different distances in front (x<0) and behind (x>0) the grid surface (x=0, marked by the vertical dotted line) for the approaching velocity of ≈17.3 $m \cdot s^{-1}$ and aligned with the central bar of the grid for the four grid angles.

Fig. 6 gives an overall view of the flow field measured by the CTA probes in front of and behind the Drop 4 grid at an angle of 60° and with an approaching velocity equivalent to 3 kn. The overall flow pattern is similar for all grids, velocities and grid angles to the one presented. An exception is the grid angle of 90°, were no deflection occurs.

The magnitude of the velocity is scaled by the approaching flow velocity $u_0$ and is illustrated in Fig. 6 by a colour contour plot. The flow direction is indicated by vectors starting at the measurement position. As expected from theory, the flow velocity in front of the grid is decreased and continues to decrease with increasing distance behind the grid. In front of the grid, there is a notable difference in the flow velocity along the grid bars. In close proximity to the lower frame member the velocity is increased, whereas near the upper frame member the velocity is decreased. It is believed that the flow through the grid is decreased in the upper region because the flow field is affected by the flow stagnation in front of the upper bar of the grid frame. For the velocity increase in the lower part, it is supposed that the flow separates at the edge of the lower bar of the grid frame and the emerging wake region constricts the flow, which results, according to the law of mass flow balance, in an increase of the flow velocity.

By inspecting the flow vectors in Fig. 6, it can be noted that the flow is slightly deflected upwards in front of the grid. At the measurement points closest to the back of the grid the deflection is reduced in comparison to the front. The strongest change in flow direction was measured at the position farthest downstream (distance grid measurement point 735 mm). However, the results of a numerical flow simulation (not published yet) show that this strong change in direction is attributed to the wake of the bars from the grid frame.

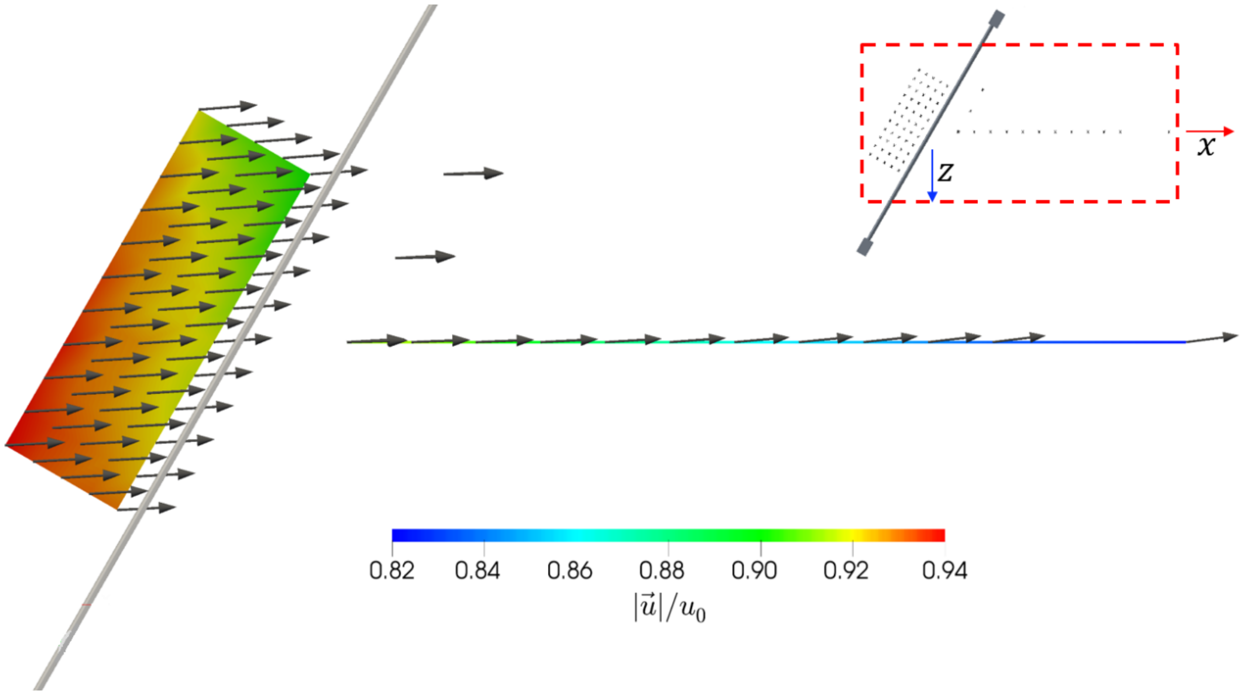


**Figure 6.** Grid Drop 4 at 60°, $\boldsymbol{u_0}$ ≈17.3 m/s (equivalent to ~3 kn). 2D vector and velocity contour plot. Vectors point in the direction of the flow, colour contours represent the magnitude of velocity scaled by the approaching flow velocity $\boldsymbol{u_0}$.

As visible in Fig. 7, the flow velocity along the front of the grid ($u_t$), is less affected by the grids inclination. Furthermore, the magnitude of the flow component is in the order of the tangential flow component of the approaching flow ($u_{t0} = u_0 \cdot \cos\alpha$), i.e. around 1. Thus, the flow along the grid, which transports the catch, may be estimated by

(16) $$u_t = u_0 \cdot \cos\alpha.$$

Moreover, all grids showed a decrease in the tangential component just behind them in relation to the tangential component just in front of the grid, although the Drop 4 grid showed a lower reduction than all other grids. The Drop 4 grid showed an average decrease of 3.4% (±1.6%, standard deviation), while the Rectangular grid showed an average decrease of 6.3% (±3.2%), Drop 8 5.5% (±1.4%), and Cylindrical 7.8% (±1.7%).

Inspecting the plots of the normal component of the velocity (Fig. 7) it can be noted that it is of the same magnitude in front of and behind the grids. This was expected due to the conservation of the mass flow through the grid. The grids with lower porosity (Cylindrical and Drop 8) showed a reduction in the velocity's normal component in relation to the normal component of the approach velocity of around 30%. A lower relative reduction of around 10% was observed for the grids with higher porosity (Rectangular and Drop 4). Thus, the normal component can be approximated by

(17) $u_n = 0.7 \cdot u_0 \cdot \sin \alpha$ for grids with a porosity of 0.4 and

(18) $u_n = 0.9 \cdot u_0 \cdot \sin \alpha$ for grids with a porosity of 0.6.

The normal component of the flow, which passes through the grid and should transport the undersized catch, is slightly higher at lower angles. At lower angles, the intersection of a plane which is spanned by the $y$-axis and the flow direction at the grid results in a more elongated grid bar shape that the flow has to follow. Thus, the form resistance decreases with decreasing grid angle and, therefore, allowing for a higher flow velocity at lower angles.

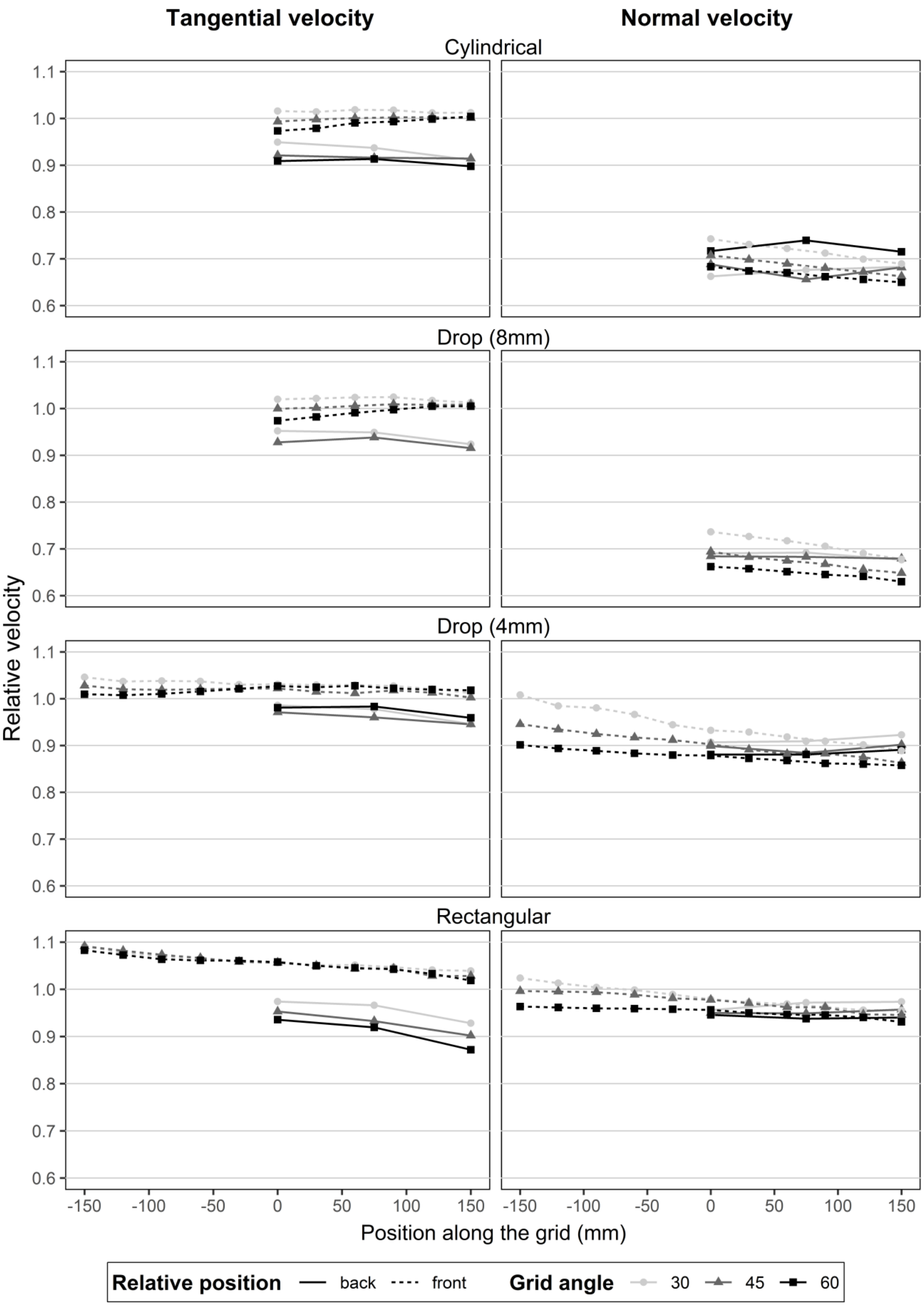


**Figure 7.** Tangential ($u_T$) and normal ($u_N$) velocity components at different positions along the grid. Position along the grid $t = 0$ is the centre of the grid.

## Discussion

The results presented here show that grid porosity is an important factor to consider when designing or selecting a sorting grid for a given fishery. At low porosity values, the water is simply rejected by the grid, thus greatly reducing the water flow through the grid. Evaluating the limiting values of the grids porosity, 0 and 1, how the porosity affects the flow becomes comprehensible. A porosity of zero represents a solid plane, whereas a porosity of 1 implies that no grid is present. The improved hydrodynamic performance of grids with higher porosity has also been described by Riedel and DeAlteris (1995) and Grimado (2006).

The shape of the bars in a grid was found to affect the hydrodynamics of the grid, although to a lesser extent than grid porosity. The overall similarity in the results obtained between the Drop 8 and Cylindrical bars showed that the drop shape was not designed properly. Indeed, bluff bodies with a high width-to-length ratio entail a high form resistance since the flow will separate from the body surface forming a wake region. Contrary, streamlined bodies with a low width-to-length ratio have a low form resistance since the flow follows the body surface. The design of the drop shape bars has a too high width-to-length ratio to have a positive effect on the resistance. It is presumed that the flow separation took place at a similar location as on the cylindrical grid bar, resulting in a similar resistance. Furthermore, the separation of flow was promoted by a small edge at the transition of the cylindrical part to the triangle part of the drop shaped grid bar. Therefore, the fin had no effect. It is recommended that care should be taken during the production of the grid bars to achieve a smooth surface and smooth transitions between geometries. A somewhat unexpected result was that the grid with the rectangular shaped grid bars performed best. However, this result could be explained by the porosity been highest for this grid, the width-to-length ratio 3.3 times lower than for the Drop 4 grid and, due to the rounded corners, the wake region potentially been smallest.

The angle of the grids in relation to the direction showed to be a less important factor concerning the hydrodynamics of the grids than their porosity. However, it is an important variable which needs to be carefully adjusted to achieve the sorting characteristics aimed for. The static pressure measurements show, at lower grid angles, a lower increase of static pressure in front of the grid, which correlates to a higher flow in front of the grid. However, since the investigated grids had a fixed height, the area that faced the flow decreased with decreasing inclination, thus resulting in a smaller overall resistance to the flow. Therefore, it is supposed that the lower static pressure in front of the grids is not attributed to the changed surface contour the flow has to follow, but to the smaller overall area that faces the flow at lower grid angles. However, further investigations have to be carried out to provide clarification.

The variation of the approach velocity showed to have nearly no effect on the hydrodynamic performance within the investigated range. The range of investigated velocities was based on the towing speeds commonly observed in commercial crustacean demersal trawl fisheries. Riedel and DeAlteris (1995) also observed this negligible effect of the flow velocity on the grid's hydrodynamics, even though lower velocities (between 1 to 2 knots) were tested in that study.

In this study, we investigated solely the hydrodynamics of the grid. However, the sorting performance of a grid will also depend on, among other factors, the biology of the target species, e.g. physical and behavioural characteristics, as well as the flow conditions in front of a grid when mounted in a trawl. In the case of shrimp sorting grids, the flow through it is highly relevant since shrimps have been described as having a passive behaviour inside the trawl, and being transported mostly by the water flow, especially small shrimp (Polet 2002; He and Balzano 2012). This is especially the case for brown shrimps, as fatigue sets in after around 15 tail-flips (Hagerman and Szaniawska 1986), where for each tail flip, swimming speeds (0.4 to 1.1 m.s-1), and distances covered per tail flip (20 to 80 mm) are limited (Arnott et al. 1998). Thus, it is likely that brown shrimp have little to no swimming capacity when reaching the aft end of the trawl. Therefore, a flow too strong through a grid, coupled with too little flow being deflected along the grid's surface, can potentially lead to loss of commercial sized catch. Individuals of lengths close to the upper limit of the sorting range may be squeezed through the bars due to the strong flow. If a good balance between flows through and along the grid exists, these individuals will be dragged along the grid surface towards the opening of the grid. Furthermore, a strong flow through the grid might also cause clogging issues due to part of the catch becoming stuck to the grid bars without being able to move. On the other hand, if the flow along the grid is too high, the sorting capacity of the grid will be affected, since small shrimps would simply follow the flow towards the opening of the grid without contacting it. The results presented here, allow for the calculation of the flow velocities in front of the grid dependent on an approaching flow velocity and the grids inclinations (Eq. 16, 17 and 18). However, further research is needed to obtain information about the interaction of shrimp, flow velocities and sorting grid designs to be able to find the optimal balance between the flow through and along grids.

In our experimental setting, the flow through the system was homogenous and was only affected by the grid. In contrast, when mounted inside a trawl, the water flow velocity approaching the grid will not be the same as the one entering the trawl or the towing velocity. This can especially be the case for fisheries where sieve nets are used. Sieve nets are nets with large mesh placed inside the trawl to guide large by-catch species and debris towards an outlet in the trawl. These by-catch reduction devices will reduce the flow that continues towards the end of the trawl since it directs part of the flow to the outlet and out of the trawl (Polet et al. 2004) although, due to its large meshes, the water flow deflected should be minimal. Another modification usually associated to grids is a guiding or lifting panel; this panel usually consists of small mesh netting used to guide the catch towards the grid to maximize the contact probability between the catch and grid. It has previously been shown that the water flow is greatly reduced due to this small mesh netting (Gjøsund et al. 2013).

A further issue affecting the flow field in front of the grid is the netting surrounding the grid. Contrary to the experimental setting, the netting will prevent a free flow around the sorting grid and hence, affecting the flow in front of and behind the grid. It is not known to what extent the surrounding netting, sieve net and guiding panel alter the flow field in front of the net. However, knowledge of the flow field in front of the net is a prerequisite to be able to adjust the sorting gird to work effectively.

A general recommendation for which one of the investigated grids should perform better in a fishing scenario cannot, due to complexity of factors affecting hydrodynamics inside a trawl, be provided yet. However, our results show that, in general, low porosity grids should be avoided, since the flow through and in front will decrease and thus reduce the sorting capabilities and increase the probability of becoming clogged. Furthermore, the performance of proceeding selective devices will be affected due to these low flow issues, as reported for dual grid systems (He and Balzano 2012; Larsen et al. 2018). If the investigated grids are assessed solely according to this hydrodynamic point of view, the Rectangular grid performs best. However, even though the Drop 4 grid has slightly worse hydrodynamics than the Rectangular grid, it may still have a better selective performance since the maximum length of constricted space between the drop shaped bars is less than for the rectangular bars. This means that the likelihood for the catch to get stuck between the bars might be less for the drop shape, thus decreasing the probability of clogging issues. In addition, when the rectangular shaped grid bars are not aligned with the flow, side forces will be induced and the advanced performance the grid showed may vanish. Moreover, the drop shape when compared to cylindrical bars adds structural strength due to its elongated shape, this being particularly important when considering thinner bar diameters. Another point to consider is, when considering the width and shape of the bars tested, the thicker bars together with the shape of the leading edge may help to orientate and then guide the shrimp through the grid, whereas a thinner bars result in more grid bars per total grid width and thus adds more points of contact for a shrimp to be held onto the front face of the grid. Even though it is important to understand specific characteristics of a grid such as hydrodynamic performance, when designing and mounting a grid in a trawl it is important to consider all perspectives. Nevertheless, this study allowed shedding light in different aspects of a grids hydrodynamics such as the importance of porosity, angle and shape of cross section of a grid. It also allowed the authors to provide a “rule of thumb” for the expect flow velocity of the normal and tangential components of the flow in the area close to the front side of the grid surface.

*Future work*

In future work, the interaction between shrimps and grids should be analyzed. When and how do shrimps become stuck? Which bar shapes guide the shrimp best? Which minimum flow velocity along the grid is required so that shrimps of a given size are transported along (dependent on the grid angle)? These questions have to be answered to find an optimal balance between the flow through and along the grid and hence the optimal inclination of the grid.

In addition, it should be considered how the surrounding netting, sieve nets and guiding panels interact with the grid. For the purpose of the development of complete sorting grid sections and predictive numerical flow simulation, which may provide answers relating to the interaction of grid and surrounding net etc., it is necessary to establish loading functions describing the hydrodynamic characteristic of the grids. Furthermore, testing of the results obtained here in a fishing scenario is also important to better relate the hydrodynamics of grids to its selective performance.

**Acknowledgements**

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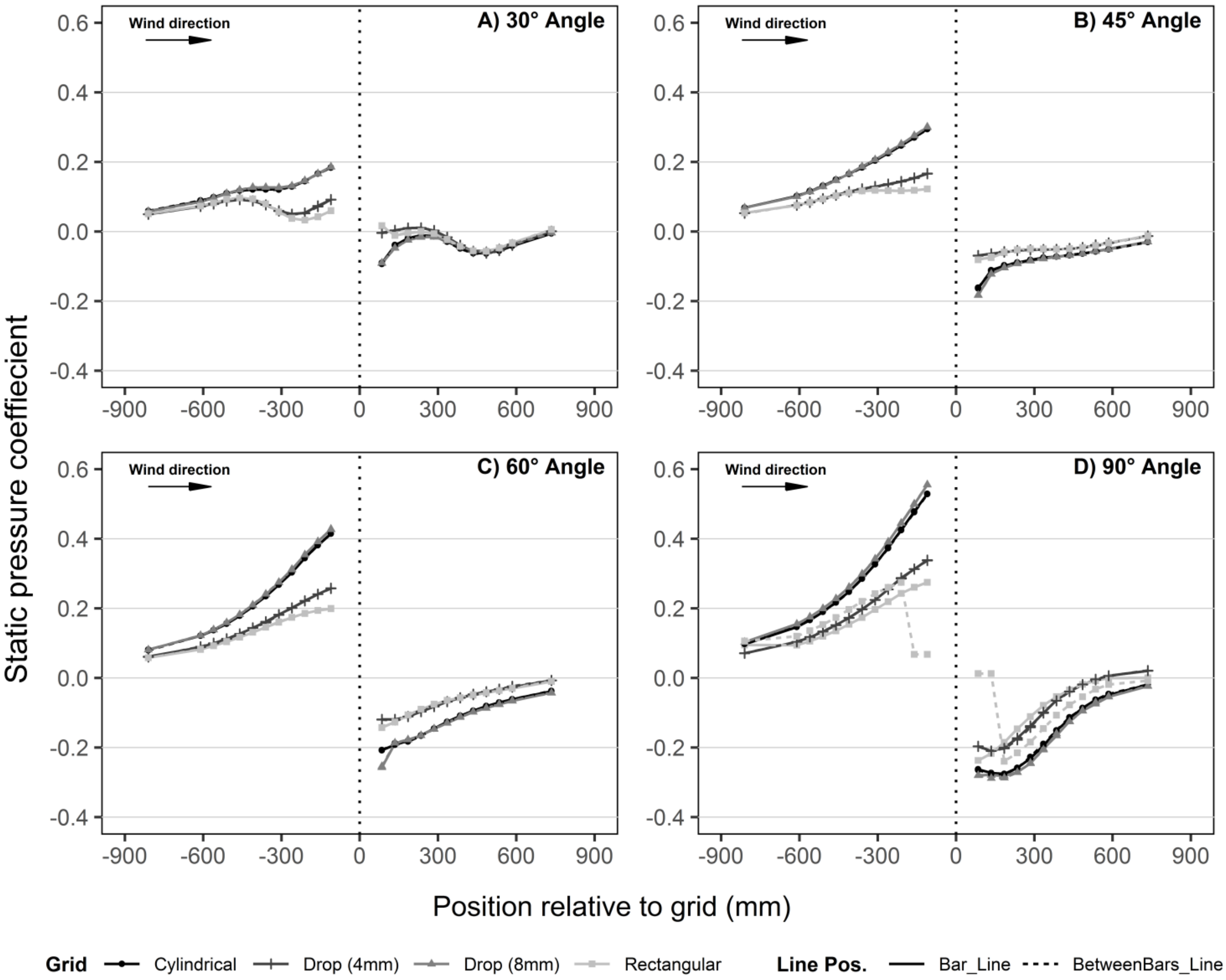
584 **Supplementary material**




585

586 **Figure S1.** Static pressure coefficient at different distances in front (x<0) and behind (x>0) the grid surface (x=0, marked
587 by the vertical dotted line) for the approaching velocity of ≈11.5 $m \cdot s^{-1}$ and aligned with the central bar of the grid for the
588 four grid angles.

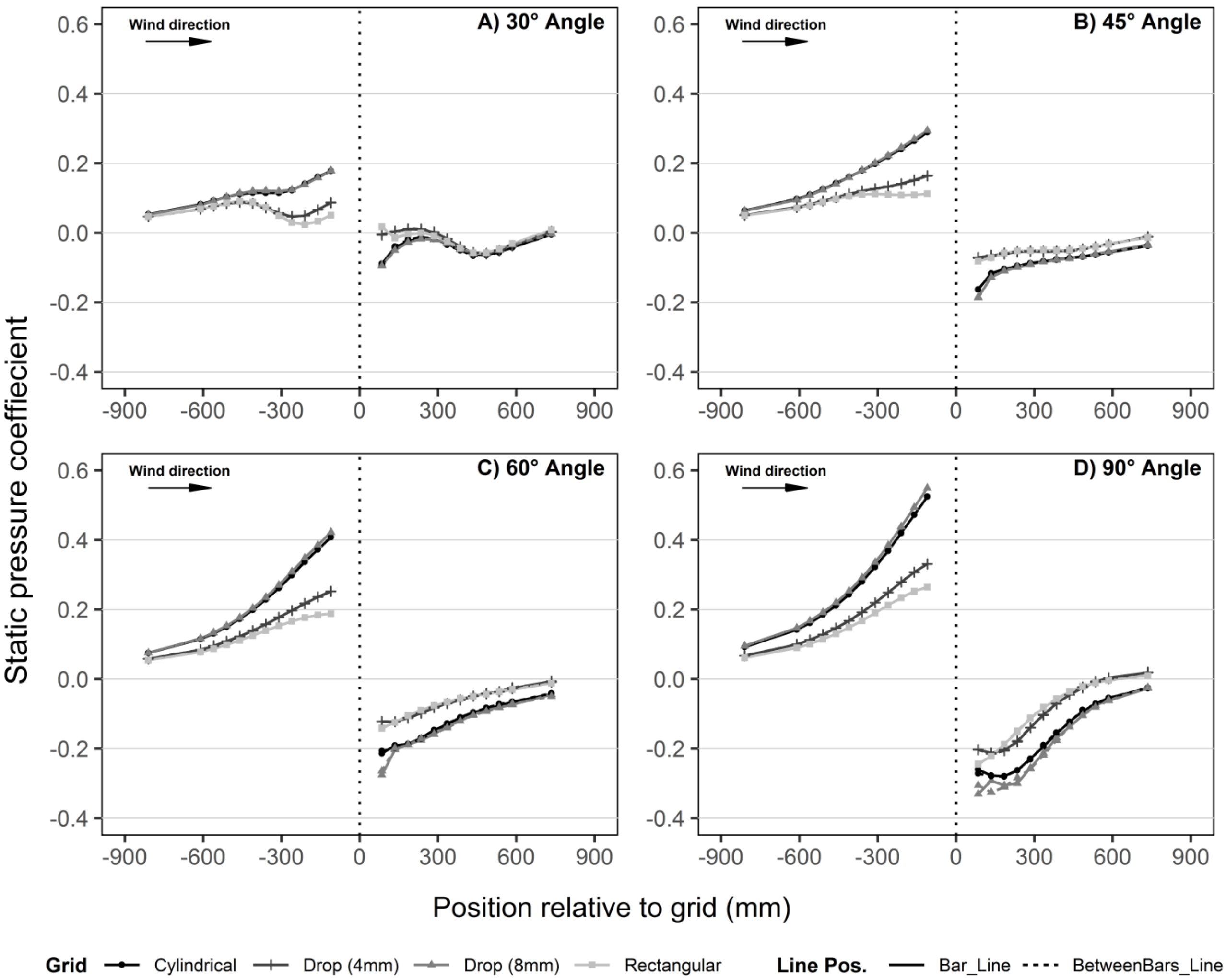



**Figure S2.** Static pressure coefficient at different distances in front (x<0) and behind (x>0) the grid surface (x=0, marked by the vertical dotted line) for the approaching velocity of ≈17.3 $m \cdot s^{-1}$ and aligned with the central bar of the grid for the four grid angles.

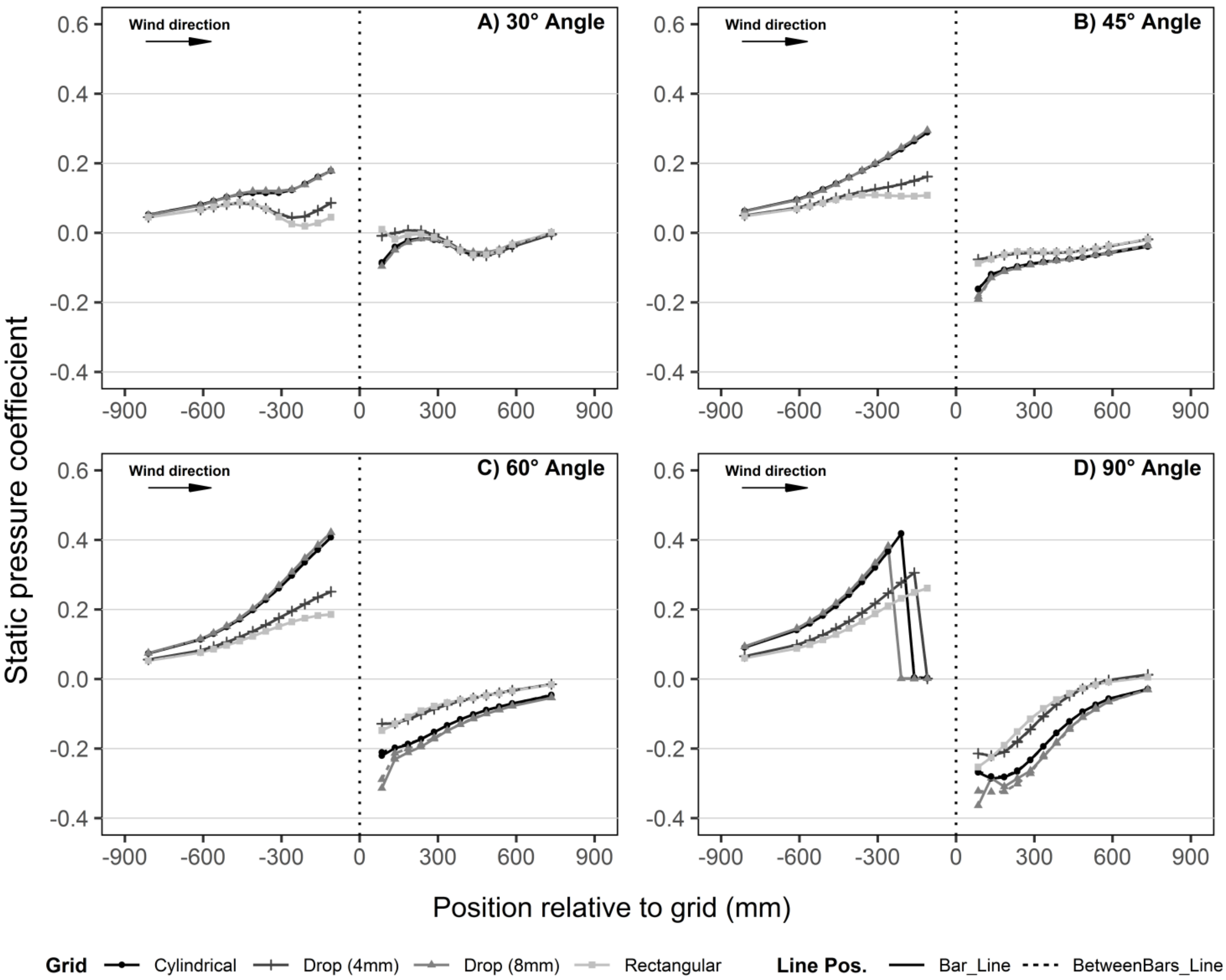



**Figure S3.** Static pressure coefficient at different distances in front (x<0) and behind (x>0) the grid surface (x=0, marked by the vertical dotted line) for the approaching velocity of ≈23.1 $m \cdot s^{-1}$ and aligned with the central bar of the grid for the four grid angles.

# Paper 4

# Testing a size sorting grid in the brown shrimp (*Crangon Crangon* Linnaeus, 1758) beam trawl fishery

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## Abstract

The North Sea brown shrimp (*Crangon Crangon* Linnaeus, 1758) fishery is a Marine Stewardship Council certified fishery. To maintain the certification, the fishery has to increase the minimum diamond mesh size of the codend used from 22 mm to 26 mm. As this increase in mesh size could result in a substantial loss of marketable size brown shrimp, a combination of a size sorting grid with a bar spacing of 6 mm and a 22 mm codend was proposed as a possible alternative to the 26 mm codend. The objective of the proposed gear was to release undersized shrimp before they reach the codend, while potentially limiting the loss of marketable size shrimp. Therefore, the aim of this study was to investigate the size selective performance for brown shrimp of this potential new gear. The results showed that the grid successfully allowed for the escape of shrimp under the commercial size of 50 mm. Moreover, the combination of the grid and a 22 mm diamond mesh codend, with an estimated L50 of 44.9 mm and a selection range of 15.6 mm, showed that it can be a potential alternative to the 26 mm diamond mesh codend.

**Keywords:** Size sorting grid, brown shrimp, *Crangon cragon*, selectivity

## Introduction

The brown shrimp (*Crangon crangon* Linnaeus, 1758) beam trawl fishery is one of the largest and most important fisheries in the North Sea, consisting of approximately 550 beam trawlers with annual catches between 30000 to 35000 tonnes (ICES, 2016; Stäbler *et al*., 2016; Tulp *et al*., 2016). Since the mid-1980s, The Netherlands, Germany, and Denmark have been responsible for the majority of the annual landings, accounting for approximately 90% (ICES, 2016).

Fisheries targeting brown shrimp are largely unregulated in terms of landings and effort, with no Total Allowable Catch (TAC), fishing-effort restrictions or minimum landing size set for this species (Steenbergen *et al*., 2015; Tulp *et al*., 2016; Addison *et al*., 2017). However, under the European Union (EU) Regulation No 850/98 it is mandatory to use sieve nets to reduce bycatch and codends with a minimum diamond mesh size of 16 mm (Revill and Holst, 2004a; Addison *et al*., 2017), although most vessels currently use 22 mm mesh size as part of the Marine Stewardship Council (MSC) brown shrimp management plan (Addison *et al*., 2017). Additional management measures can be applied at the national level, such as limiting the number of licences given, defining closed areas to the fishery and restricting the number of fishing days (Addison *et al*., 2017; Steenbergen *et al*., 2017). Moreover, even though there is no minimum landing size for brown shrimp, individuals smaller than 50 mm are usually discarded since they have no market value (Revill and Holst, 2004a; Addison *et al*., 2017).

In 2016, the Dutch, German, and Danish producer organizations initiated a MSC certification process for a sustainable and well-managed fishery; by December 2017 the three brown shrimp fisheries received the MSC certification until December 2022 (Addison *et al*., 2017). Since there are no EU stock management regulations for the brown shrimp, the producer organizations set a self-regulating plan including harvest control rules to meet the “sustainable fishing” principle of MSC (Steenbergen *et al*., 2017). These harvest control rules specify the number of hours each vessel can fish on a weekly basis and are determined on the catch rates of brown shrimp in the previous month. When catch rates fall below certain thresholds the fishing effort is reduced accordingly (Addison *et al*., 2017; Steenbergen *et al*., 2017). Also, the codend mesh size currently used in the fishery was found to be too non-selective by the MSC (Addison *et al*., 2017). Indeed, the L50, length with 50% retention probability, for a mesh size with 22 mm is approximately 40 mm (Polet, 2000; Santos *et al*., 2018) thus, with the currently used mesh size a substantial fraction of the catch is below the commercial size of 50 mm and is subsequently discarded.

A recent study has shown that a codend with a 26 mm diamond mesh size has a L50 of 46.4 cm (Santos *et al*., 2018); thus showing great potential to reduce the catches of non-marketable sized brown shrimp. Based on those results, to maintain the MSC certification, it was included in the management plan that the fishery increases the minimum codend mesh size used from 22 mm to 26 mm by 2020 (Addison *et al*., 2017). This increase in codend mesh size is to be introduced progressively, with an intermediate increase in mesh size from 22 to 24 mm before the final 26 mm (Addison *et al*., 2017). However, Santos *et al*. (2018) also showed that increasing the mesh size to 26 mm will result in the loss of brown shrimp above the marketable size. Therefore, concerned with this loss of marketable size brown shrimp, the Danish fishermen proposed to use a size sorting grid with a bar spacing of 6 mm in conjunction with a codend of 22 mm diamond mesh as a potential alternative to the 26 mm diamond mesh codend. The objective of the grid is to release undersized shrimp before they reach the codend, while potentially limiting the loss of marketable size shrimp. Grids are commonly used in shrimp fisheries as bycatch reduction devices (Broadhurst, 2000; Polet, 2002; Graham, 2003; Fonseca *et al*., 2005). More recently, grids have also been successfully tested for size sorting of the target species in a northern prawn (*Pandalus borealis* Krøyer, 1838) fishery (He and Balzano, 2012; 2013). Therefore, the aim of this study was to investigate the size selective performance for brown shrimp when using a grid with 6 mm bar spacing and a 22 mm diamond mesh codend. In particular, three research questions were addressed: i) How is the selective performance of the test gear compared to the 22 mm mesh size codend currently in use?; ii) How is the selective performance of the test gear compared to the 26 mm mesh size codend?; and iii) What is the test gear's overall size selectivity for brown shrimp?

## Material and Methods

*Grid description*

**Figure 1. Size sorting grid for brown shrimp (left panel) with 6 mm bar spacing, mounted in an extension piece (right panel) in front of the codend. Notice the entry to the codend in the top and the guiding panel in the bottom (black net).**

The size sorting grid consisted of a hardened plastic frame made from nylon (PA6) and was 50 cm wide and 73 cm long (figures 1 and 2). The grid's bars were 3.9 mm thick and 63 cm long, and constructed out of glass-fibre reinforced plastic. The spacing between the bars was 6 mm (see figure 2 for more detailed information). The grid was mounted in an extension piece made from 22 mm diamond-mesh netting at an angle of 50°. A guiding panel, made with 20 mm diamond-mesh netting, was placed in front of the grid to guide the catch towards the lower part of the grid to increase the contact rate of the catch with the grid surface. Individuals small enough to pass through the grid are selected out of the gear, while larger individuals are led into the codend through the passage above the grid. This passage is 15 open meshes high and 54 open mesh wide on the top (figure 1). To ensure the extension piece retained its shape during fishing while not interfering with the release of the escapees, a 200 mm diamond mesh section was placed behind the grid in the bottom panel of the extension piece.

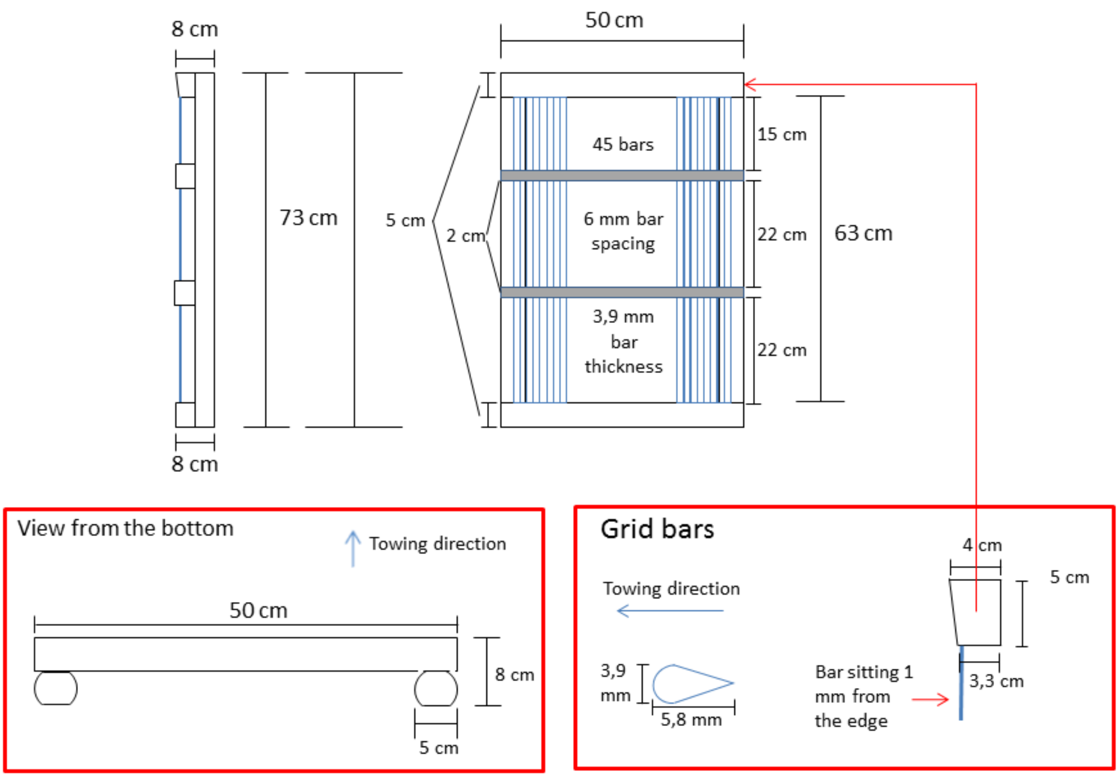


**Figure 2. Description of the 6 mm size-sorting grid with drop shaped bars that were used during this study.**

*Sea trials description*

Three consecutive sea trials were conducted off the coast of southwest Denmark in the North Sea, on board the commercial vessel E 426 “Rune Egholm”, a twin beam trawler with 18 m LOA and 125 kW main engine power, from 21$^{st}$ of January to the 25$^{th}$ of January, 2019. The vessel was equipped with two identical 10 m wide beam trawls, 15 m long and with a vertical opening of 0.6 m. In both trawls, a mandatory sieve net of 70 mm mesh size was mounted (see e.g. Revill and Holst, 2004b). In all three trials, the combination of the 6 mm size sorting grid with a standard 22 mm diamond mesh codend (22.1±0.5 mm), hereafter referred to as SG6M22, was used as the test gear. In the first and second trials, SG6M22 was tested, respectively, against a 22 mm (22.4±0.5 mm) and 26 mm (26.1±0.5 mm) diamond mesh codend, hereafter referred to as M22 and M26, respectively. Both trials were conducted as catch comparison trials (e.g. Krag *et al.*, 2014) where the two beam trawls were towed in parallel to compare the catch efficiency of both gears. In the third trial, SG6M22 was tested against an 11 mm diamond mesh codend, hereafter referred to as M11. In this trial, M11 was used as the control to estimate the absolute selectivity of SG6M22 using the paired-gear method described in Wileman *et al*., 1996. It was not possible to accurately measure the mesh sizes of M11, since the meshes size range was within the lower limit of measurable sizes by the Omega gauge (10 mm ± 1 mm precision). Nevertheless, M11 was assumed to be non-selective for all relevant sizes of brown shrimp as described in Santos *et al*. (2018), thus, its catches being representative of the population available for SG6M22.

For every haul, approximately 4 kg random samples were taken from the unsorted catch of each gear and frozen for subsequent length measurement on land. These samples were then unfrozen in the laboratory, all brown shrimp sorted and weighed, and from the total sample a random sub-sample of around 1000 individuals was weighed and length measured. Total length measurements were obtained by digital image analysis by use of ridge detection in ImageJ, as described in Santos *et al*. (2018). The total lengths obtained were rounded down to the nearest millimetre for the subsequent statistical analyses.

*Statistical analyses*

Using the numbers and sizes of shrimp length measured per codend and haul we determined, for trial 1 and 2 separately, whether there was a significant difference in the catch efficiency averaged over hauls between the baseline gear and test gear.

The number of shrimp per length class caught in the different codends in trial 1 and 2 were used to evaluate the relative size catch efficiency for brown shrimp of the test gear in relation to the baseline gears. To assess the relative length-dependent catch efficiency between the test and baseline gears, we used the method described in Herrmann *et al*. (2017) and compared the catch data for the two types of gears fished simultaneously. This method models the length-dependent catch comparison rate ($CC_l$) summed over hauls.

$$\mathrm{CC}_{il} = \frac{\sum_{i=1}^{m}\left\{\frac{\mathrm{nt}_{li}}{q\mathrm{t}_i}\right\}}{\sum_{i=1}^{m}\left\{\frac{\mathrm{nt}_{li}}{q\mathrm{t}_i}+\frac{\mathrm{nb}_{li}}{q\mathrm{b}_i}\right\}} \tag{1}$$

where $nT_{li}$ and $nB_{li}$ represent the number of shrimp of each length class *l* length measured in the i-th haul for the test and baseline gear respectively. $qT_i$ and $qB_i$ are the corresponding sampling factors for test and control gear respectively quantifying the fraction of the total catch in the i-th haul being length measured. *m* represents the total number of hauls. The functional form for the catch comparison rate $CC(l, \boldsymbol{v})$ (the experimental being expressed by equation 1), was obtained using maximum likelihood estimation (MLE) by minimizing the following expression:

$$-\sum_{l}\left\{\sum_{i=1}^{m}\left\{\frac{nt_{li}}{qt_i}\times ln\big(CC(l,\boldsymbol{v})\big)+\frac{nb_{li}}{qb_i}\times ln\big(1.0-CC(l,\boldsymbol{v})\big)\right\}\right\} \tag{2}$$

where $\boldsymbol{v}$ represents the parameters describing the catch comparison curve defined by $CC(l, \boldsymbol{v})$. The outer summation in the equation is the summation over the length classes *l*. When the catch efficiency of the test gear and baseline gear is similar, the expected value for the summed catch comparison rate would be 0.5. The experimental $CC_l$ was modelled by the function $CC(l, \boldsymbol{v})$, on the following form:

$$CC(l,\boldsymbol{v}) = \frac{exp\big(f(l,v_0,\ldots,v_k)\big)}{1+exp\big(f(l,v_0,\ldots,v_k)\big)} \tag{3}$$

where *f* is a polynomial of order *k* with coefficients $v_0$ to $v_k$. The values of the parameters $\boldsymbol{v}$ describing $CC(l, \boldsymbol{v})$ are estimated by minimizing equation (2), which are equivalent to maximizing the likelihood of the observed catch data. We considered *f* of up to an order of 4 with parameters $v_0$, $v_1$, $v_2$, $v_3$ and $v_4$. Leaving out one or more of the parameters $v_0 \ldots v_4$ led to 31 additional models that were also considered as potential models for the catch comparison $CC(l,\boldsymbol{v})$. Among these models, estimations of the catch comparison rate were made using multi-model inference to obtain a combined model (Burnham and Anderson, 2004; Herrmann *et al*., 2017). The ability of the combined model to describe the experimental data was evaluated based on the *p*-value. This *p*-value, which was calculated based on the model deviance and the degrees of freedom, should not be <0.05 for the combined model to describe the experimental data sufficiently well, except from cases where the data were subjected to over-dispersion (Wileman *et al*., 1996).

Based on the estimated catch comparison function $CC(l, \boldsymbol{v})$ we obtained the catch ratio, $CR(l, \boldsymbol{v})$, between the two gears by the following relationship:

$$CR(l,\boldsymbol{v}) = \frac{CC(l,\boldsymbol{v})}{\left(1-CC(l,\boldsymbol{v})\right)} \qquad (4)$$

The catch ratio is a value that represents the relative catch efficiency of the test gear when compared to that of the baseline gear. Thus, if the catch efficiency of both gears is equal, $CR(l,\boldsymbol{v})$ should always be 1.0. Moreover, $CR(l,\boldsymbol{v})$ = 1.5 would mean that the test gear is catching 50% more shrimp with length *l* than the baseline gear, while $CR(l,\boldsymbol{v})$ = 0.7 would mean that the test gear is only catching 70% of the shrimp with length *l* compared to the baseline gear. The confidence limits for the catch comparison curve and catch ratio curve were estimated using a double bootstrapping method (Herrmann *et al*., 2017). This bootstrapping method accounted for between-haul variation by selecting *m* hauls with replacement from the pool of hauls during each bootstrap repetition. Within-haul uncertainty in the size structure of the catch data was accounted for by randomly selecting shrimp with replacement from each of the codends (test and baseline) separately. The number of shrimp selected from each codend was the same as the number of shrimps length measured from the codend. To correctly account for the increased uncertainty due to subsampling, the data were raised by sampling factors after the inner resampling. However, contrary to the double bootstrapping method describe in Herrmann *et al*. (2017) the outer bootstrapping loop in the current study accounting for the between haul-variation was performed paired for the test and baseline gears. Thus, taking full advantage of the experimental design in which both types of gear were deployed simultaneously. Moreover, by using the multi-model inference in each bootstrap iteration, the method also accounted for the uncertainty in model selection. We performed 1000 bootstrap repetitions and calculated the Efron 95% (Efron, 1982) confidence limits (CIs). To identify sizes of shrimp with significant differences in catch efficiency, we checked for length classes in which the 95% confidence limits for the catch ratio curve did not contain the value 1.0. Moreover, size-integrated average values for the catch ratio ($CR_{average}$) were estimated directly from the experimental catch data as indicators for the relative selective performance of the gears test using the following equations:

$$
\begin{aligned}
CR_{average-} &= 100 \times \frac{\sum_{l<ML}\sum_{i=1}^{m}\left\{\frac{nt_{li}}{qt_i}\right\}}{\sum_{l<ML}\sum_{i=1}^{m}\left\{\frac{nb_{li}}{qb_i}\right\}} \\
CR_{average+} &= 100 \times \frac{\sum_{l\geq ML}\sum_{i=1}^{m}\left\{\frac{nt_{li}}{qt_i}\right\}}{\sum_{l\geq ML}\sum_{i=1}^{m}\left\{\frac{nb_{li}}{qb_i}\right\}}
\end{aligned}
\qquad (5)
$$

$CR_{average-}$ and $CR_{average+}$ compare the number of shrimp caught under and over the minimum commercial size (ML= 50 mm) between the test and the baseline gear for each trial. Values of 100 indicate that the test gear catches the same number of shrimp than the baseline gear. Therefore, $CR_{average-}$ should be as low as possible while $CR_{average+}$ should be as high as possible. Estimates of $CR_{average-}$ and $CR_{average+}$ are only considered statistically significant if the estimated 95% CI for each indicator does not include the value of 100.

Finally, to investigate how well the size selectivity of the test and baseline gears matched the size structure of shrimp in the area fished, a fishing sustainability indicator (*DnRatio*) was estimated directly from the experimental catch data for each gear tested by:

$$DnRatio_{test} = 100 \times \frac{\sum_{l<ML} \sum_{i=1}^{m} \left\{ \frac{nt_{li}}{qt_i} \right\}}{\sum_{l} \sum_{i=1}^{m} \left\{ \frac{nt_{li}}{qt_i} \right\}}$$
$$DnRatio_{baseline} = 100 \times \frac{\sum_{l<ML} \sum_{i=1}^{m} \left\{ \frac{nb_{li}}{qb_i} \right\}}{\sum_{l} \sum_{i=1}^{m} \left\{ \frac{nb_{li}}{qb_i} \right\}} \quad (6)$$

where the outer summation in the nominator includes the size classes in the catch that were under the marketable size of brown shrimp, while in the denominator the outer summation is for all size classes in the catch. *DnRatio* is therefore the ratio between discards and total catch in weight, thus it should be as low as possible, with 0 being the best possible situation where no discards occur. The value of *DnRatio* is affected by both the size selectivity of the gear and the size structure of the shrimps in the fishing grounds. Therefore, it provides an estimate that is specific for the population fished and it cannot be extrapolated to other areas and seasons. The CIs for the average $CR_{average-}$, $CR_{average+}$ and $DnRatios$ were estimated using the same double bootstrap routine used to estimate the CIs of the $CC(l,\boldsymbol{v})$ and $\mathrm{CR}(l,\boldsymbol{v})$ curves.

Owing to the experimental design, the catch data from the test and control gears was collected simultaneously in the same hauls, thus they can be regarded as paired. The catch data from individual hauls was used to estimate the average size selectivity for the test gear by pooling data over hauls and applying the paired gear estimation method (Wileman *et al*., 1996). The average size selectivity in the test gear was therefore estimated based on the catch data summed over hauls by minimizing the following equation:

$$-\sum_{l} \sum_{i=1}^{m} \left\{ nT_{li} \times ln\left( \frac{SP \times r(l,\boldsymbol{v})}{SP \times r(l,\boldsymbol{v}) + 1 - SP} \right) + nB_{li} \times ln\left( 1.0 - \frac{SP \times r(l,\boldsymbol{v})}{SP \times r(l,\boldsymbol{v}) + 1 - SP} \right) \right\} \quad (7)$$

where $nT_{li}$ and $nB_{li}$ represent the number of shrimp of each length class *l* length measured in the i-th haul for the test and control gear respectively. $qT_i$ and $qB_i$ are the corresponding sampling factors for test and control gear respectively quantifying the fraction of the total catch in the i-th haul being length measured. *m* represents the total number of hauls. *SP* is the split factor quantifying the sharing of the total catch between the test and the control gear (Wileman *et al*., 1996). Minimizing equation (7) is equivalent to maximizing the likelihood for the observed experimental data. $\boldsymbol{v}$ is a vector of parameters describing the size selection model $r(l,\boldsymbol{v})$. Since the test gear were constructed with two selection devices placed sequentially after each other, where shrimp first would have the chance of getting size selected by the grid process ($r_{grid}(l)$) and shrimp that was not selected out in the grid process would be size selected subsequently by the codend meshes (($r_{codend}(l)$)) (figure 1). To be able to account for this dual and sequential nature of the size selection in the test gear we modelled the size selection in the test gear by:

$$r(l,\boldsymbol{v}) = r_{grid}\left(l,\boldsymbol{v}_{grid}\right) \times r_{codend}(l,\boldsymbol{v}_{codend}) \tag{8}$$

where $\boldsymbol{v} = \left(\boldsymbol{v}_{grid}, \boldsymbol{v}_{codend}\right)$. The rationale behind (8) is that a shrimp will only be retained in the test gear if it is retained in both the grid size selection process and in the codend size selection process. Since the codend consisted of a single mesh type and size we assumed that the size selection for the codend process could be described by a traditional s-shaped size selection model with increasing retention probability for shrimps of increasing size. Therefore, for the codend size selection process we considered four different models (Wileman *et al*., 1996):

$$r_{codend}(l,\boldsymbol{v}_{codend}) = \begin{cases} logit(l, L50_{codend}, SR_{codend}) \\ probit(l, L50_{codend}, SR_{codend}) \\ gompertz(l, L50_{codend}, SR_{codend}) \\ richard(l, L50_{codend}, SR_{codend}, 1/\delta_{codend}) \end{cases} \tag{9}$$

The first three models in (9) have two parameters $L50_{codend}$ (length of shrimp with 50% retention probability conditioned it entered the codend) and $SR_{codend}$ (=$L75_{codend} - L25_{codend}$) whereas the last model have one additional parameter $1/\delta_{codend}$ that enable a s-shaped curve with asymmetry (Wileman *et al*., 1996). For more details on the different models please see appendix.

For the grid process in (8), besides considering the same s-shaped models as for the codend equation (9), we also considered the potential situation that only a fraction C of the shrimp will make contact with the grid to be size selected by it. Further, we considered the situation that none of the shrimp did contact the grid. Based on these considerations, we ended considering a total of nine different models for the grid process:

$$r_{grid}(l, \boldsymbol{v}_{grid}) =$$

$$\begin{cases} logit(l, L50_{grid}, SR_{grid}) \\ probit(l, L50_{grid}, SR_{grid}) \\ gompertz(l, L50_{grid}, SR_{grid}) \\ richard(l, L50_{grid}, SR_{grid}, 1/\delta_{grid}) \\ clogit(l, C_{grid}, L50_{grid}, SR_{grid}) = 1.0 - C_{grid} + C_{grid} \times logit(l, L50_{grid}, SR_{grid}) \\ cprobit(l, C_{grid}, L50_{grid}, SR_{grid}) = 1.0 - C_{grid} + C_{grid} \times probit(l, L50_{grid}, SR_{grid}) \\ cgompertz(l, C_{grid}, L50_{grid}, SR_{grid}) = 1.0 - C_{grid} + C_{grid} \times gompertz(l, L50_{grid}, SR_{grid}) \\ crichard(l, L50_{grid}, SR_{grid}, 1/\delta_{grid}) = 1.0 - C_{grid} + C_{grid} \times richard(l, L50_{grid}, SR_{grid}, 1/\delta_{grid}) \\ 1.0 \end{cases} \quad (10)$$

The last option in equation (10) accounts for the option to consider that the grid might not contribute at all to the size selection process in the test gear. Further, it enables modelling the combined selection process according to (8) by a simple s-shaped selection curve. In total, based on the combinations of equations (9) and (10) in equation (8), 36 models were considered to describe the combined size selectivity for grid + codend in the test gear. The 36 models were tested against each other and the one with the lowest AIC value (Akaike's Information Criterion; Akaike, 1974) was selected. MLE using equations (7) with (8) to (10) requires pooling experimental data over hauls. This results in stronger data for average size-selectivity estimation at the expense of not considering explicit variation in selectivity between hauls (Fryer, 1991). To account correctly for the effect of between-haul variation when estimating uncertainty in size selection, the same double bootstrap method described above was used. Specifically, the confidence limits for the size selection curve and the associated selection parameters were estimated using a double bootstrapping method for paired-gear data. We performed 1000 bootstrap repetitions and calculated the Efron 95% (Efron, 1982) CIs for the size selection curve and the associated parameters. The ability of this size selection model to describe the experimental data was evaluated based on the p-value, which quantifies the probability of obtaining by coincidence at least as big a discrepancy between the experimental data and the model as observed, assuming that the model is correct. Therefore, the p-value calculated based on the model deviance and the degrees of freedom should not be <0.05 for the selection model to describe the experimental data sufficiently well unless the data has over-dispersion (Wileman *et al*. 1996). All analyses described here were done using the statistical analysis software SELNET (Herrmann *et al*., 2012).

## Results

A total of 36 valid hauls were conducted during the three sea trials, with a total of 12 hauls for each (Table 1). Fishing operations were kept as similar as possible to normal commercial fishing activities during the first two trials, with a mean towing time of 2 hours per haul and a mean towing speed of 3.3 kn. For the third trial, due to fact that a non-selective codend (M11) was used, the duration of the hauls was reduced to approximately one hour instead of the normal two hours due to the potential large catches in the M11 codend. Moreover, a total of 76046 shrimps were length measured for this study, with sub-sampling factors being on average 2.4%, but ranging from 0.5 to 7.4%.

**Table 1. Summary of the valid hauls for the three sea trials. Values within parenthesis are the range of the data.**

| | **Trial 1** | | **Trial 2** | | **Trial 3** | |
|---|---|---|---|---|---|---|
| **Gear** | 6 mm Grid + 22 mm codend | 22 mm codend | 6 mm Grid + 22 mm codend | 26 mm codend | 6 mm Grid + 22 mm codend | 11 mm codend |
| **No. of hauls** | 12 | | 12 | | 12 | |
| **Mean haul duration (min)** | 120 (115-130) | | 120 (120-120) | | 63 (40-100) | |
| **Mean towing speed (kn)** | 3.3 (3.0-3.5) | | 3.3 (2.8-3-4) | | 3.3 (3.1-3.5) | |
| **Mean fishing depth (m)** | 5.8 (3.0-8.0) | | 6.8 (5.0-9.0) | | 7.6 (6.0-10.0) | |
| **Mean shrimp catch size (kg)** | 93.8 (16.8-264.7) | 105.4 (22.2-257.1) | 74.7 (27.8-127.4) | 75.2 (32.4-138.7) | 33.3 (12.9-65.2) | 51.0 (20.5-87.3) |
| **Number measured (no.)** | 12464 | 12741 | 12654 | 12504 | 12739 | 12944 |
| **Mean sub-sample factor (%)** | 2.6 (0.5-6.6) | 2.1 (0.5-5.4) | 1.8 (0.9-5.0) | 1.8 (0.8-4.6) | 3.5 (1.3-7.4) | 2.2 (1.1-6.7) |

Datasets from trials 1 and 2 were analysed and catch comparison models fitted to assess the relative selective performance of the SG6M22 in relation to M22 (figure 3) and M26 (figure 4), respectively. For both models, *p*-values lower than 0.05 (*p*-values ≤ 0.005 for both models) were found. Therefore, residuals of the models were plotted against length (not shown) and how the models describe the experimental data visually checked (figures 3 and 4) to assess the quality of the fit. No patterns were found in the residuals and the models were found to describe well the trends in the data; which indicates that the poor fit statistics obtained are due to over-dispersion in the data. The over-dispersion in the data is likely to be due to the low sub-sampling factors (Fryer, 1991). Moreover, the different indicators for brown shrimp were obtained for the trials 1 and 2 (Table 2).

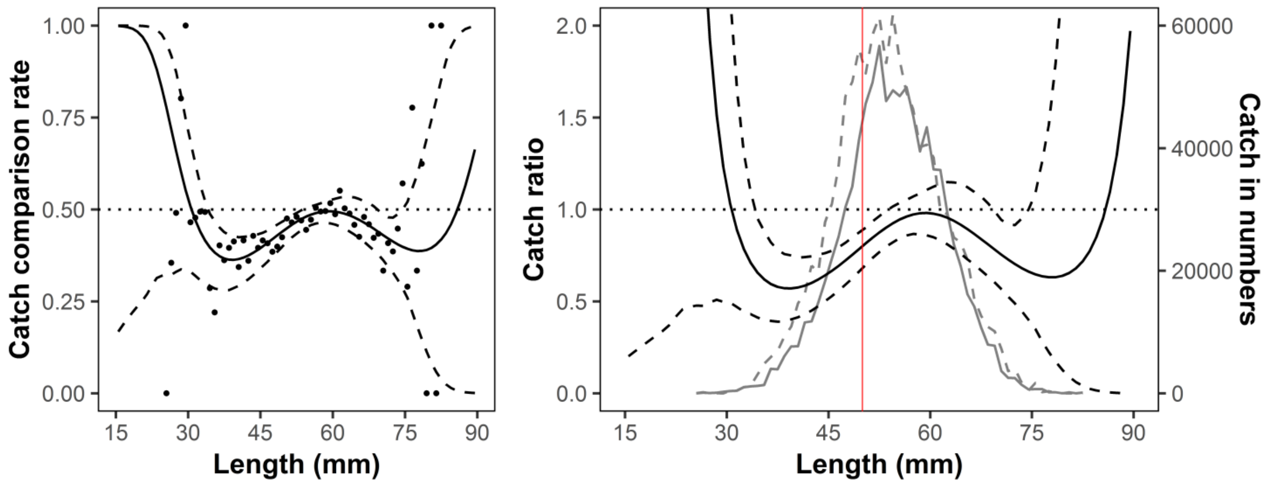


**Figure 3. Estimated average catch comparison with experimental data points (left panel) and catch ratio (right panel) curves (solid black line) and 95% confidence intervals (broken black lines) for brown shrimp obtained when comparing the size sorting grid with 6 mm bar spacing and codend with a 22 mm mesh size (SG6M22; test) to a codend with a 22 mm mesh size (M22; baseline). Dotted grey horizontal lines represent when both gears are fishing equally efficient. Grey lines represent the catch length structure of brown shrimp for SG6M22 (solid grey line) and M22 (broken grey line). The red vertical represents the minimum commercial size for brown shrimp (50 mm).**

The catch comparison and catch ratio curves obtained from trial 1 when comparing SG6M22 and M22 are shown in figure 3. The SG6M22 caught significantly less brown shrimp for lengths between 34 and 52 mm than M22. According to the catch ratio curve, the largest reduction in the catch of brown shrimp occurred for the length of 40 mm; at this length SG6M22 caught at least ~26% less brown shrimp and on average ~42% less. At the minimum commercial market size of 50 mm, SG6M22 caught at least ~10% less and on average ~18% less. Moreover, the estimated curves also show a significant decrease in the catch of lengths between 69 and 73 mm for the

SG6M22; for the length of 72 mm this gear caught at least ~8% less (on average ~30% reduction). No significant differences were found for the remaining lengths classes. Furthermore, the $CR_{average-}$ estimated for the first trial show that SG6M22 significantly reduced the catch of brown shrimp smaller than 50 mm by 33.3% (95% CI from 47.2 to 22.2%; table 2). Although no significant difference was found for the catch of shrimp with length above 50 mm, the results indicate that SG6M22 caught on average 8% less marketable shrimp ($CR_{average+}$ for trial 1 in table 2).

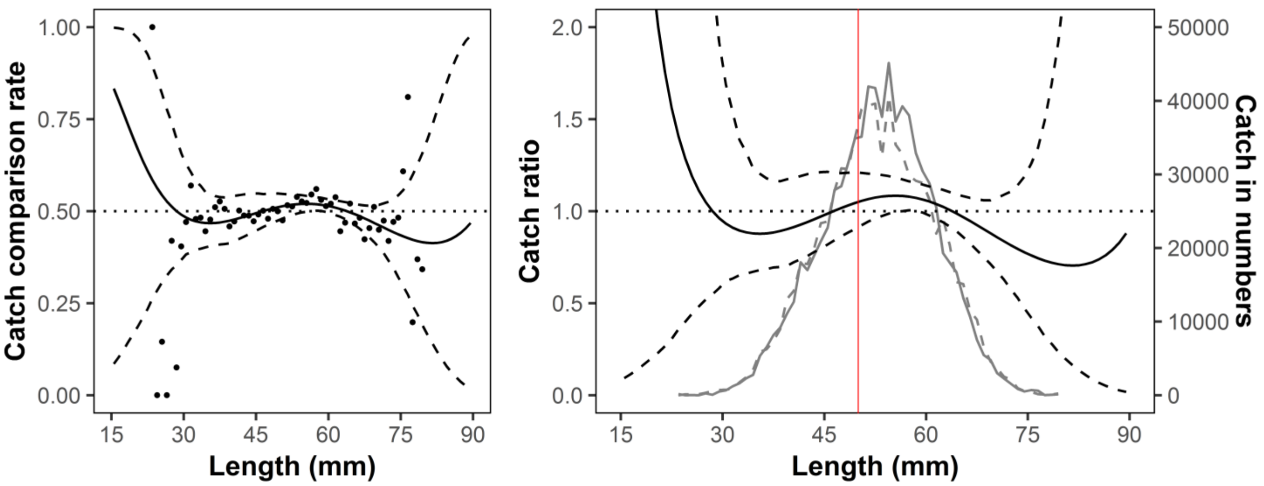


**Figure 4. Estimated average catch comparison with experimental data points (left panel) and catch ratio (right panel) curves (solid black line) and 95% confidence intervals (broken black lines) for brown shrimp obtained when comparing the size sorting grid with 6 mm bar spacing and codend with a 22 mm mesh size (SG6M22; test) to a codend with a 26 mm mesh size (M26; baseline). Dotted grey horizontal lines represent when both gears are fishing equally efficient. Grey lines represent the catch length structure of brown shrimp for SG6M22 (solid grey line) and M26 (broken grey line). The red vertical represents the minimum commercial size for brown shrimp (50 mm).**

In the second trial, SG6M22 was compared to the M26, and the obtained catch comparison and catch ratio curves are shown in figure 4. For two length classes, 57 and 58 mm, a slightly significant difference was found, with SG6M22 catching more shrimp for these length classes than M26. Nevertheless, for the lengths between 46 and 62 mm, where the bulk of the catch is, there seems to be a non-significant indication that SG6M22 catches more brown shrimp. No significant differences were found for all the other lengths between the catch size structures from SG6M22 and M26. Furthermore, the indicators for the second trial show no significant difference between SG6M22 and M26 (table 2). Nevertheless, there is the indication that SG6M22 caught on average 4% less undersize and 5% more marketable brown shrimp than M26.

**Table 2. Estimated values for the different indicators for brown shrimp. Values within parenthesis are the Efron 95% confidence intervals. $CR_{average-}$ and $CR_{average+}$ are the size-integrated average values for the catch ratio of all length classes, respectively, under and above the minimum marketable size of brown shrimp (50 mm). DnRatio represents the discard ratio in numbers.**

| | Trial 1 | | Trial 2 | |
|---|---|---|---|---|
| **Gear** | 6 mm Grid + 22 mm codend | 22 mm codend | 6 mm Grid + 22 mm codend | 22 mm codend |
| **n <50 mm (in thousands)** | 244.8 (139.8-362.2) | 367.3 (233.9-508.0) | 282.8 (215.4-344.7) | 293.9 (221.4-366.1) |
| **n >=50 mm (in thousands)** | 695.7 (404.7-1033.7) | 755.7 (459.5-1072.5) | 539.2 (430.1-652.2) | 512.6 (399.1-642.3) |
| **DnRatio (%)** | 26.0 (23.5-28.5) | 32.7 (30.5-35.8) | 34.4 (30.8-38.1) | 36.4 (32.3-40.9) |
| $CR_{average-}$ **(%)** | 66.7 (52.8-77.8) | | 96.2 (80.6-117.0) | |
| $CR_{average+}$ **(%)** | 92.1 (81.1-102.0) | | 105.2 (96.6-114.2) | |

The catch sharing curve obtained from comparing the selective performance of SG6M22 to that of a non-selective codend, M11, in the third trial allowed estimating the overall absolute selectivity of the gear SG6M22 (figure 5). As for the catch comparison models, the fit statistics from the catch sharing model indicated issues with the model fit. The analysis of the model residual and visual analysis of the model fit suggested that the poor fit statistics obtained were again due to over-dispersion in the data. The best model, with the lowest AIC, describing the overall absolute selectivity of SG6M22 was a combination of Richards model for the first process (grid) and Gompertz model for the second process (codend). A $L_{50}$ of 44.9 mm (95% CI from 42.4 to 49.6 mm), a $SR$ of 15.6 mm (95% CI from 13.3 to 23.6 mm) was estimated for the absolute selectivity of SG6M22. A split of 0.51 (95% CI from 0.46 to 0.60) was estimated from the catch sharing model. The estimated $L_{50}$ of SG6M22 is below the 50 mm minimum commercial size for brown shrimp, while the retention probability for this length was estimated to be 73% (95% CI from 53 to 83%).

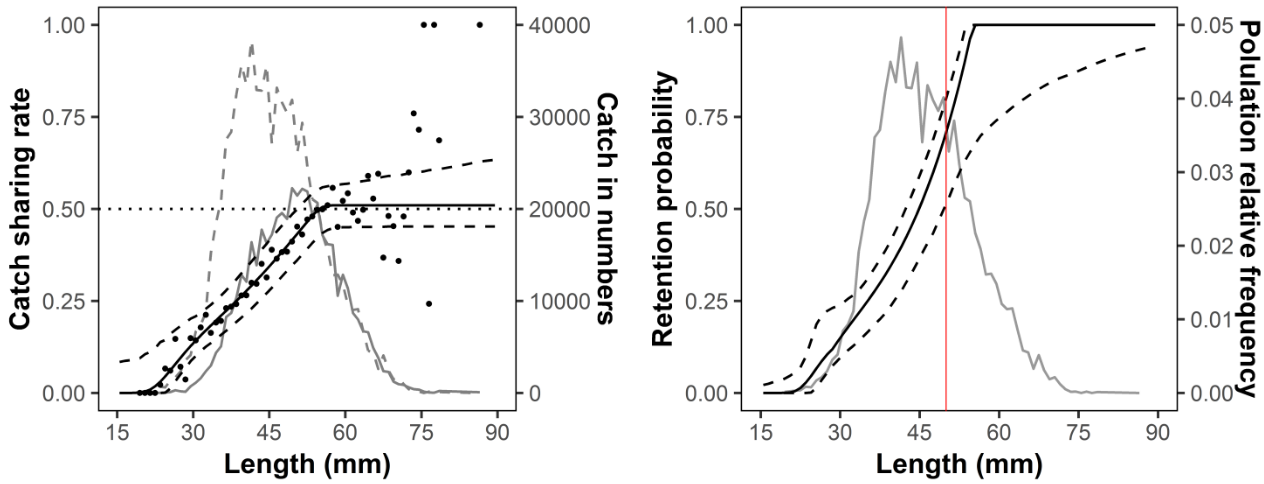


**Figure 5. Estimated catch sharing rate with experimental data points (left panel) and absolute size selectivity (right panel) curves (solid black lines) and 95% confidence intervals (broken black lines) obtained for brown shrimp when comparing the size sorting grid with 6 mm bar spacing and codend with a 22 mm mesh size (SG6M22) with a non-selective codend with a 11 mm mesh size (M11). Dotted grey horizontal lines represent when both gears are fishing equally efficient. Grey lines in left panel represent the catch length structure of brown shrimp for SG6M22 (solid grey line) and M26 (broken grey line). Grey line in the right panel represents the relative length structure of the population encountered by the trawl. The red vertical represents the minimum commercial size for brown shrimp (50 mm).**

## Discussion

Since the trials were performed on-board a commercial vessel, under commercial conditions and on common fishing grounds, the results obtained in this study are applicable to the fishing industry and provide useful information for managers. The potential usefulness of a sorting grid to reduce the catch of small brown shrimp was demonstrated in this study. Here, the combination of a sorting grid with a bar spacing of 6 mm and a diamond mesh codend with a mesh size of 22 mm (SG6M22) was shown to reduce the catch of small brown shrimp when compared to the currently legislated codend with a mesh size of 22 mm diamond mesh (M22). As the sorting grid was the sole difference between both fishing gears, the difference in the catch structures from both gears can only come from the effect of the grid. Thus, the sorting grid allowed for the escape of small shrimp before they reached the codend. This reduction of undersized shrimp was expected, since the sieves used on-board the commercial vessels to sort out small shrimp and fish as discards also have an average bar spacing of 6 mm (Aviat *et al*., 2011). Moreover, sorting grids used as a way to reduce the catch of smaller shrimp have also been successfully tested in a northern prawn fishery in Gulf of Maine (He and Balzano, 2007; 2012).

When considering the selective performance of SG6M22 compared to the codend required to maintain the MSC certification, 26 mm diamond mesh codend (M26), the results show the gear are equivalent in terms of retention of shrimp below the marketable size. This means that SG6M22 could be an alternative for the fishermen to meet the MSC requirements. However, the uptake by the fishermen of this more complex gear design would only be justified if it prevented the loss of marketable size catch. On this the results of this study were not conclusive, but there was a strong indication that SG6M22 catches slightly more marketable size brown shrimp than the M26. Indeed, a significant increase in catch rate was found for few lengths above the marketable size of 50 mm and the indicators obtained also seem to support this indication of increased catch of marketable size shrimp, although not significantly. This indication could derive from the fact that a portion of the catch will not enter in contact with the surface of the grid, as shown from previous studies (e.g. Stepputtis *et al*., 2016). A portion of the catch will therefore only be subjected to the size selection of the M22 codend which has a lower L50 and SR than the M26 (Santos *et al*., 2018). In contrast, a fraction of marketable size shrimp in the portion of the catch that contact the grid is selected out. This loss of shrimp above marketable size is evident when considering the results of the third trial, where the overall selectivity of SG6M22 was estimated. The estimated absolute selectivity of SG6M22 showed that full retention is achieved at the length of 55 mm, while that is achieved earlier (approx. 51.5 mm) for a 22 mm diamond mesh codend (Santos *et al*., 2018). However, the results of the absolute selectivity trial partly contrast with the results obtained in the first trial, when SG6M22 was compared to M22. Here, a significant loss of larger shrimp (69 to 73 mm) was estimated by the model. We believe that this result is most likely an artefact due to the large sub-sampling, which greatly increases the uncertainty around the length classes less represented in the catch.

The size sorting grid presented in this study was designed to maximize the flow through the grid by reducing the width of the bars, thus increasing its porosity, and by using drop shaped bars. Veiga-Malta *et al*. (Under submission (Paper 3 in this thesis)) showed that, for the same bar spacing of 6 mm, porosity is indeed an important factor to reduce the resistance of the grid to the flow of water. This raises the question of how should grids be specified in the legislation? In the case of grids for reduction of by-catch, setting maximum bar spacing for a grid should be enough (e.g. Council Regulation (EC) No 27/2005) as fishermen will not reduce the bar spacing since they risk losing a portion of the target species. For example, in Polet (2002), issues with water flow and clogging in grids have been associated with a reduction in the catch of target species. On the other hand, when the objective is to avoid the capture of undersize individuals, setting only a minimum bar spacing could lead to highly ineffective size sorting grids to be legally used in a fishery. For example, increasing the bar thickness from 4mm to 8mm has been shown to reduce the water flow in front of a grid by approximately 30 % (Veiga-Malta *et al*., Under submission (Paper 3 in this thesis)). This reduction in water flow, could lead to a reduction in the selective performance of the grid.

In conclusion, we found that the combination of a size sorting grid with a bar spacing of 6 mm and a codend constructed from 22 mm diamond mesh is a viable alternative to the 26 mm diamond mesh codend which is to be introduced into the fishery as part of the MSC plan for brown shrimp. Despite the higher complexity of the gear design tested in this study, no issues with the gear arose during the fishing process, such as clogging issues or twisting of the gear. Furthermore, the fishermen were satisfied with the handling of the gear both during fishing, retrieval processes and on board the vessel. To maximize the potential of the gear selective performance, thus potential uptake by the fishermen, further investigation should be performed to minimize the loss of marketable size shrimp while maximizing escape of small shrimp. Estimating the catch's contact rate with the grid would allow guiding the direction for future research. For example, further reduction in bar spacing if further improvement in contact rate is difficult, or a combination of increasing contact rate with the grid and decreasing codend mesh size could be tested in future experiments.

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## Appendix

### Size selection models

The basic size selection models used in the present study are presented below (Wileman *et al*.,1996).

The Logistic (*Logit*) size selection curve is the cumulative distribution function of a logistic random variable:

$$Logit(l) = \frac{\exp(a + bl)}{1 + \exp(a + bl)}$$

Where *a* and *b* are the parameters of the model. $Logit(l)$ quantifies the length-dependent retention probability with *l* being the length of the fish or shrimp. The above equation can be rewritten in terms of the parameters *L50* and *SR*, where:

$$L50 = -\,{}^{a}\!/_{b}\ ,\quad \mathrm{SR} = \frac{2 \times \ln(3)}{b} = \frac{\ln(9)}{b}$$

Leading to:

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

The *Probit* size selection curve (Normal probability ogive) is the cumulative distribution of a normal random variable,

$$Probit(l) = \Phi(a + bl)$$

Where Φ is the cumulative distribution function of a standard normal random variable, and *a* and *b* are the parameters of the model. The *Probit* can be rewritten in terms of parameters *L50* and *SR*, where:

$$L50 = -\,{}^{a}\!/_{b}\ ,\quad \mathrm{SR} = \frac{2 \times Probit(0.75 - 0.25)}{b} \approx \frac{1.349}{b}$$

Leading to:

$$Probit(l, L50, SR) \approx \left( \frac{exp\left(\frac{1.349}{SR}(l - L50)\right)}{1 + exp\left(\frac{1.349}{SR}(l - L50)\right)} \right)$$

The *Gompertz* size selection curve is expressed by the following equation:

$$Gompertz(l) = \exp(-\exp(-(a + bl)))$$

It can be rewritten in terms of the parameters *L50* and *SR*, where:

$$L50 = \frac{-\ln(-ln(0.5)) - a}{b} \approx \frac{0.3665 - a}{b}\ ,\quad \mathrm{SR} = \frac{\ln\left(\frac{\ln(0.25)}{\ln(0.75)}\right)}{b} \approx \frac{1.573}{b}$$

Leading to:

$$Gompertz(l, L50, SR) \approx \exp\left( -\exp\left( -\left(0.3665 + \frac{1.573}{SR}(l - L50)\right)\right)\right)$$

The last of the four basic size selection curves considered here is the *Richard* curve, which has an extra parameter, named *1/*δ. This parameter controls the degree of asymmetry of the curve. When δ = 1 the curve is identical to the *Logit* curve. The equation for a Richard size selection curve is the following:

$$Richard(l) = \left(\frac{\exp(a + bl)}{1 + \exp(a + bl)}\right)^{1/\delta}$$

Rewritten in terms of the parameters *L50* and *SR* with:

$$L50 = \frac{Logit\left(0.5^{\delta}\right) - a}{b}$$

$$\mathrm{SR} = \frac{Logit\left(0.75^{\delta}\right) - \ Logit\left(0.25^{\delta}\right)}{b}$$

Leading to:

$$Richard(l, L50, SR, \delta) = \left( \frac{exp\left(Logit\left(0.5^{\delta}\right) + \left(\frac{Logit\left(0.75^{\delta}\right) - \ Logit\left(0.25^{\delta}\right)}{SR}\right)(l - \ L50\right)}{1 + exp\left(Logit(0.5^{\delta}) + \ \left(\frac{Logit(0.75^{\delta}) - \ Logit(0.25^{\delta})}{SR}\right)(l - \ L50\right)} \right)$$