DEVELOPMENT OF SEABED FRIENDLY BOTTOM TRAWLS

by

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ABSTRACT

Concerns over the impacts of fishing practices, especially bottom trawling, on the ocean environment have been expressed at the local, national and international scale. While physical alterations of the seabed by bottom trawling are known to occur, the biological effects on benthic communities and their recovery rates depend on substrate types, depth, and natural disturbance in the fishing area, as well as how trawl gears are designed and operated. In this thesis, I investigate different key research aspects regarding the subject of development of seabed friendly bottom trawls, in particular shrimp trawling in Newfoundland and Labrador, Canada. The complementary use of different research approaches (e.g., underwater video observations, numerical modeling and simulation, flume tank testing, and at-sea experiments) were applied for each of the research questions.

First, I investigated the behavioural interactions of individual snow crab in response to the rockhopper footgear of a traditional inshore shrimp trawl used in Newfoundland and Labrador, Canada. I found that snow crab were quickly overtaken under the footgear of the approaching trawl and over half of the snow crab (i.e., 54%) observed experienced an encounter with the rockhopper footgear components. The majority of the snow crab observed appeared to be aware of the trawl and were actively responding and/or reacting to the approaching threat. Second, the strengths and limitations of different commercially available trawl simulation software (i.e., DynamiT, SimuTrawl, and Trawl Vision PRO) in terms of design capability, simulation capability, and reliability of results, were investigated and interpreted. The study provides valuable

knowledge and reference for stakeholders (e.g., gear designers, researchers, and educators) who are considering using numerical simulation methods to optimize their gear design concepts during the early stages of development of seabed friendly bottom trawls (e.g., predict expected mechanical stresses of trawl components on the seabed). Next, I addressed the question of how well computer simulation and flume tank testing of scale engineering models actually predict full-scale at-sea performance of bottom trawls. The results demonstrated that the complementary use of two or three methods should be encouraged for assisting the gear development cycle given their own weakness and merits. For instance, the flume tank testing method was successfully utilized to estimate the percentage of contact area made by trawl footgear with the seabed, while at-sea experiments were not designed to measure such impacts. Moreover, I clarified that the precision and accuracy of the predictions depends on many factors. Thus, thoroughness and care must be emphasized in order to reduce bias in predicted performance. Finally, I examined the effectiveness of a reduced seabed impact footgear (i.e., drop chain) over a traditional rockhopper footgear on identical bottom trawls targeting northern shrimp (*Pandalus borealis*) in Newfoundland and Labrador, Canada. The results demonstrated that seabed impacts of shrimp trawling can be reduced if the trawl footgear is made lighter and/or designed to have less contact with the seabed. In particular, it was revealed that with the experimental drop chain footgear trawl we are able to reduce the interaction or encounter of snow crab.

In summary, the knowledge presented in this thesis is believed to significantly contribute to the research and development of low-impact bottom trawls both in theoretical and practical aspects. While the potential impact of bottom trawling activities on habitats and benthic communities is not easy to predict and characterize for various reasons, I do believe that further development and application of fishing gears and techniques that reduce impacts on seabed habitats and associated benthic communities will be essential to achieve ecosystem objectives.

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Chapter 1. Introduction and Overview

Bottom trawling is a common method of industrialized fishing throughout the world's oceans. It is used widely in commercial fisheries that target species living on or near the seabed (Gabriel et al., 2005 and He, 2007), with an estimated 22% of the total fish production (Kelleher, 2005) harvested using bottom trawls. However, concerns over the impacts of fishing practices, particularly bottom trawling, on the ocean environment have been expressed at the local, national and international scale (Morgan and Chuenpagdee, 2003; Rice, 2006; Fuller et al., 2008). The growing demand for certification of fisheries by eco-labels such as the Marine Stewardship Council are a strong indication that consumers and seafood retailers are increasingly concerned with the sustainability of fisheries, especially those involving trawling (Washington and Ababouch, 2011; OECD, 2012; Foley, 2013). Bottom trawling uses numerous types of gear designs, sizes, rigging and operational methods. One of the key features is that the gear must remain physically in contact with the seabed for successful operation (i.e., provides mechanical spread and herding of target species), which can result in removal or damage of sedentary living communities and benthic habitats. Ecological impacts can be varied depending on the location and timing of the fishery (Edinger et al., 2007). Documented effects are varied, including reductions in biomass of targeted and non-targeted species, reductions in biodiversity, changes in species richness, community structure, sediment resuspension, benthic perturbation, and loss of habitat (see review by Kaiser et al., 2003). Many countries have produced fishery management strategies to mitigate and manage these effects, including identification of vulnerable marine areas, area closures, fishing effort reductions, gear modifications and restrictions, and limits on bycatch of particular species (e.g., Valdemarsen and Suuronen, 2003; Valdemarsen et al., 2007; Gillett, 2008; He and Winger, 2010).

The following chapter describes the characteristics of the main components of bottom trawls that affect the seabed and benthic communities, provides an overview of the current state-of-knowledge on the ecological impacts of bottom trawling, reviews development of low-impact bottom trawls, and provides a brief outline of the research presented in this thesis.

1.1 Bottom Trawls

1.1.1 Overview

A bottom trawl is a towed fishing gear that is designed to catch fish, shrimp, or other target species that live on or in close proximity to the seabed. Bottom trawls can be classified into three separate catogories based on how their horizontal opening is maintained, including: 1) beam trawls (uses a beam to spread the trawl horizontally), 2) bottom otter trawls (uses a pair of otter boards or trawl doors to expand the trawl horizontally through hydrodynamic and ground sheering forces), and 3) bottom paired trawls (uses a pair of fishing vessels/trawlers to keep the trawl open horizontally) (FAO, 1990). The otter trawl is the most common method of bottom trawling in the world for targeting demersal fish and shellfish species (He, 2007). For many shrimp and prawn fisheries, it is the only method which is economically viable (Valdemarsen et al., 2007). This trawling method can be considered as a further development of beam trawls which first appeared in the late 1880s, but suffered the disadvantage of reduced mouth opening (Gabriel et al., 2005). The otter trawl was first introduced in 1894 by the engineer James Robert Scott who patented a spreading device to replace the awkward beam on a beam trawl (Watson et al., 1984). Today, otter trawling, more commonly referred to as bottom trawling, is practiced in nearly all of the world's coastal states, and can be found to occur in estuaries, coastal regions and the high seas to depths of 2000 m or more. The term 'otter trawl' has largely fallen into disuse, and so here forward, I will use the term 'bottom trawl' throughout.

A typical bottom trawl is designed and engineered as a system of parts, consisting of a pair of trawl doors, sweeps and bridles, and trawl net, all of which works together with predictable geometry, proper trawl performance, and capture efficiency (Figure 1.1). The trawl net is constructed of a series of tapered netting panels selvedged together to create a funnel-shaped bag. Common elements include wings, square, body, extension, and codend. A number of floats are distributed along the headline to provide positive bouyancy and open the trawl vertically. The footgear or groundgear is typically constructed of chain, rubber, or steel components and is designed to provide a sinking force, as well as protection for the net as the trawl is towed over the seabed. The following sections (1.1.2 to 1.1.6) characterize the main components of bottom trawls that could likely affect the seabed and benthic communities.

1.1.2 Trawl Doors

Trawl doors are a well developed method for maintaining the horizontal opening of a bottom trawl (Gabriel et al., 2005). They are engineered to generate hydrodynamic and shearing forces that produce lift (i.e, horizontal spread) in order to spread the mouth of a bottom trawl. To maintain an optimum spread of the trawl, it is generally essential that there is good seabed contact with the trawl doors (FAO, 1974). Trawl doors are typically rigged at an angle of attack to the water flow, producing a sand or mud cloud that travels along the sweep and bridle toward the mouth of the trawl (Figure 1.1). This produces a strong visual stimulus that can assist in the herding of targeted species into the mouth of the trawl (Wardle, 1983; Lindeboom and de Groot, 1998; Winger et al., 2010). There is a wide range of trawl door designs in different forms (i.e., flat, V-shaped, cambered, or even oval) and sizes used today in commercial fisheries depending on targeted species, fishermen preference, and/or demand for mitigating impact on the environment (Valdermarsen et al., 2007). Historically, trawl doors were simple flat plates (i.e., rectangular and wooden), known as easy to store and handle, and relied heavily on ground sheer for spreading force, that were normally longer than their height or called low aspect ratio doors (the ratio of height to width). In contrast to flat doors, newer (modern) trawl doors are constructed of high-strength steel and contain various hydrodynamic features that maximize lift, performance, and stability. For some fisheries, there has been the development of high-aspect trawl doors (Sala et al., 2009). These door designs rely very little on seabed contact for spreading the trawl and in turn usually have smaller tracks or “footprint” and much less sand cloud, or even reduced trawl resistance/fuel consumption (He and Winger, 2010 and Eayrs et al., 2012) compared to traditional (low-aspect ratio) doors which have a strong tendency to disturb the seabed and resuspend sediment in their wake (Goudey and Loverich, 1987; Gabriel et al., 2005; Valdemarsen et al., 2007).

1.1.3 Trawl Warps

Trawl warps are steel cables that connect the vessel to the trawl doors, extending from the surface to the seabed (Figure 1.1). Trawl warps usually do not contact the seabed during nornal operation. The length of the warps are typically 3-5 times the sea depth and account for an estimated 8% of total drag resistance (Folch et al., 2008). The warp-depth ratio is considered a key operational factor that is manipulated by vessel captains in order to control trawl performance, particularly when applying semi-pelagic trawling techniques (He et al., 2006; Sala et al., 2010; Rivierre et al., 2013), or being used in groundfish survey trawls to achieve and maintain stable bottom contact of the trawl doors (Walsh and McCallum, 1997). The amount of trawl warp deployed (or differences between warp lengths) can affect trawl geometry/symmetry, performance, and its ability to maintain contact with the seabed, particularly for trawl doors, sweeps/bridles, and footgear. For survey trawls, it has been shown to affect variability in trawl capture efficiency, especially for flatfish species (Weinberg and Somerton, 2006), and the level of gear penetration and contact area on the seabed.

1.1.4 Trawl Bridles and Sweeps

Bridles and sweeps are made from steel cables, which connect the trawl doors to the trawl net at the wingends (Figure 1.1). The length and angle of attack of these cables is carefully matched to the desired target species (Loverich and West, 1988). In many fisheries, target species that are outside the path of the net, but inside the path of the doors (known as the sweep zone), can be effectively herded into the path of the net (see Figure 1.2). The degree of bottom contact by these cables (bridles and sweeps) will depend upon rigging parameters (e.g., angle of attack) and target species, as well as the types of trawl doors used (high aspect-ratio vs. low aspect-ratio doors) (Goudey and Loverich, 1987 and West, 1987). Fisheries targeting flatfish tend to use longer cables (>200m) with broad angles of attack (Rose et al., 2010). Shrimp trawls and survey trawls by comparison, tend to use shorter (less than 40m) or non-existent bridles along with a narrow angle of attack (e.g., He, 2007 and Walsh et al., 2009). In some cases in order to improve the herding effectiveness as well as protect the bridles, rubber rollers - up to 15cm diameter (known as cookies) may also be attached to the bridles. The evolution of the industry toward progressively longer sweeps, together with their direct seabed contact to increase herding fish into the path of the trawl (i.e., improve flatfish catches) has created negative ecological impacts in some fisheries. Recent studies conducted to minimize such seabed contact and effects on benthic communities by raising sweeps a short distance off the bottom, have proven effective (Guyonnet et al., 2008; Rose et al., 2010; He et al., 2014).

1.1.5 Trawl Footgear

The footgear or groundgear is one of the major components of a bottom trawl. It attaches to the fishing line through a number of toggle chains and tends to directly contact the seabed (Figure 1.1). Footgear is constructed from different elements including wires, chains, spacers, rubber discs/bobbins, wheels or sphericals and in a variety of designs and sizes according to the complexity of the habitat (e.g., bottom and sea conditions) on which the trawl is towed and the species targeted (Gilkinson, 1999; Løkkeborg, 2005, He, 2007). This component of the trawl ensures close contact with the seabed and enables fishing on complex grounds (e.g., rocks and corals) without damaging the more vulnerable parts of the trawl (i.e., netting) (Gilkinson, 1999). Rockhopper footgears have become increasingly common during the past few decades, particularly in areas of hard or rugged seafloor conditions (Gilkinson, 1999). This type of footgear consists of tightly packed rubber discs strung under tension so as to encourage ‘hopping’ over boulders. They are used widely in groundfish and shrimp fisheries and are considered a major cause of habitat destruction (West, 1987 and Raloff, 1996). However various forms of what maybe considered “seabed friendly footgears” have been developed in order to reduce contact area, penetration depth, or suspension of sediment. Fishing gear technologists have developed innovative footgear components that roll over the seabed (Ball et al., 2003 and Murphy, 2014), align with the direction of tow (He and Balzano, 2009 and Munden, 2013), or simply reduce contact area/points (Brewer et al., 1996, Sheppard et al., 2004; Nguyen et al., 2015). All of these innovations can have positve effects in reducing the negative effects of trawling on the seabed.

1.1.6 Trawl Net

The trawl net is constructed of a series of tapered netting panels selvedged together to create a funnel-shaped bag (Figure 1.1). It may be two-sided (top and bottom) or four-sided (addition of sides) depending on the target fishery. Differences in design, shape, and dimensions of these panels contribute to defining the trawl shape and its engineering performance. The square provides an overhang on the top of the trawl, preventing fish from escaping over the headline. Side panels of the trawl are extended in front to form wings for herding fish into the opening of the net. The extension piece is added to improve stability of the codend immediately following it. Modern net designs are engineered to minimize seabed contact by cutting back or eliminating the lower wings and applying an upward taper for the lower bellies in order to raise themselves and the codend clear of the seabed, reducing trawl damage and seabed impact (Walsh et al., 2009). The vertical opening of the trawl is generally maintained using positive buoyancy (floats and rope) or hydrodynamic kites attached to the headline (e.g., Beutel et al., 2008), together with hydrodynamic forces on the netting while towing. From a seabed impact perspective, the trawl net is the least destructive component of a bottom trawl. A codend with large catches, however, may bring the codend down and in contact with the seabed (West, 1987 and He, 2007). Therefore, a codend cover (i.e., chafing gear made by webbing or other material) is often used to protect the codend from damage and wear (He, 2007).

1.1.7 Summary

Given their characteristics and features (see descriptions above) bottom trawls are widely recognized as one of the greatest potential gear types to negatively affect the seabed and benthic communities. In order to address this growing social concern, we must understand the negative impacts of trawling on the seabed and develop responsible harvesting strategies and gear types that minimize potential impacts. The following sections (1.2 and 1.3) review the state-of-knowledge in both regards.

1.2 Environmental Impacts of Bottom Trawls

1.2.1 Studies on Impacts of Bottom Trawling

There have been increasing globally concerns about the ecological impacts of mobile bottom contacting fishing gears (e.g., bottom trawling and dredging) on habitat destruction and the sustainability of fish stocks, endangered species, and non-targeted bycatch species during the last few decades (e.g., Martin, 1991; Sahrage and Lundbeck, 1992; Crowley, 1996; Kaiser, 1996; Berrill, 1997; Morgan and Chuenpagdee, 2003; Løkkeborg, 2005; Rice, 2006; UNGA, 2007; Fuller et al., 2008; Welsford et al., 2014). But the concern is not altogether new. Concerns over the use of mobile fishing gear (e.g., capture of juvenile fish and negative effects on benthic communitities) were expressed by fishermen in the United Kingdom and The Netherlands as early as the fourteenth century when the otter trawl was invented (de Groot, 1984 and Wardle, 1986). The first scientific impact study was carried out in the North Sea in 1938 regarding plaice fishing grounds

(Graham, 1955). However, the most comprehensive studies on the effects of towed fishing gear have been conducted in Europe since the 1970s (de Groot, 1984; Lindeboom and de Groot, 1998; Kaiser and de Groot, 2000). Of particular interest is an on-going EU-funded project '*Benthic Ecosystem Fisheries Impact Study*', known as BENTHIS, which includes a number of research institutes, fishing companies, and fishing gear manufactuerers from across Western Europe. Within the project, different fisheries are being investigated, including flatfish and shrimp fisheries with beam trawls, nephrops and roundfish fisheries with otter trawls, and shellfish fisheries with dredges. Major objectives of the project include: 1) study the vulnerability of different benthic ecosystems in European waters, 2) analyse the physical impact of the current fishing practices on benthic communitites and geo-chemical processes, and 3) study and promote technological innovations to reduce the negative impact of selected demersal fisheries (CORDIS, 2015). In addition to these, there have been several impact-related studies and reviews conducted for fishing grounds in the Northwest Atlantic (e.g., Grand Banks and Georges Bank) (Auster et al., 1996; Collie et al., 1997; Gilkinson, 1999; Nguyen et al., 2014), particularly after declines of major commercial stocks in the early 1990s (He, 2007; Lilly, 2008; Fuller et al., 2008). Scientific literature reviews provide evidence that mobile bottom gears can harm benthic organisms, reduce habitat complexity, and reduce biodiversity (Kaiser et al., 2003; Valdemarsen and Suuronen, 2003; Valdemarsen et al., 2007; Meenakumari et al., 2008; Pham et al., 2014). The concerns of trawling impacts have appeared in many popular media with increasing frequency (Gilkinson et al., 2006).

The impact of mobile bottom-contact gears (e.g., bottom trawling and dredging) on benthic communities and marine habitats has also been discussed in other forms. These include extensive reviews (Jones, 1992; Alverson, 1994; Jennings and Kaiser, 1998; Auster and Langton, 1999; Kaiser and de Groot, 2000; Moore and Jennings, 2000; Dieter et al., 2003; Mueter, 2008; Meenakumari et al., 2008; Grant, 2012), books (Collie et al., 1997; Dorsey and Pederson, 1998; Hall, 1999; NRC, 2002; Sinclair and Valdimarson, 2003; Lokkerborg, 2005; Barnes and Thomas, 2005; He and Winger, 2010), and workshops/symposiums (Anon, 2001 and ICES, 2014). Rather noteworthy, a number of working groups and study groups have been formed within the International Council for the Exploration of the Sea (ICES) in an attempt to scientifically understand and document the impacts of mobile fishing gears on the seabed and marine habitat (ICES, 1988, 1999, 2000, 2004, 2014).

In summary, many scientific investigations have been completed and others are still ongoing. Several major questions continue to be asked, including: what are the effects of bottom trawling on the seabed and benthic communities? what are the direct and indirect effects of the trawling activity? and what are the short-and long-term effects on populations, community structure, and interspecific dynamics? While physical alterations of the seabed by bottom trawling are evident (Jones, 1992; Lokkeborg, 2005; Rice, 2006), the effects of alterations on the benthic communities and recovery rates associated with gear alterations depend on substrate types, depth, towing speed, and natural disturbance in the fishing area (Valdemarsen et al., 2007). The following sections (1.2.2 and 1.2.3) review physical and biological impacts of bottom trawling.

1.2.2 Physical Impacts of Bottom Trawling

Studies on the effects of bottom trawling on the seabed (covering broad areas from the North Sea to the North Atlantic Canada to the Barents Sea and the Mediterranean Sea) tend to describe physical disturbances of the seabed as either “tracks” (up to 30cm deep) or “flattening of the seabed” (caused by sweeps, bridles, and footgear). These disturbances are typically documented using side-scan sonar and/or video observations (Krost et al., 1990; Service and Magorrian, 1997; Lindeboom and de Groot, 1998; Schwinghamer et al., 1998; Tuck et al., 1998; Currie and Parry, 1999; Smith et al., 2000; Smith et al., 2007; Humborstad et al., 2004; O’Neill et al., 2009; Lindholm et al., 2015). The computational fluid dynamic (CFD) approach has also been used to investigate the penetration depth and sediment displacement associated with each gear component (Ivanović et al., 2011) or suspension of sediment in the wake behind different gear components (van Marlen et al., 2010;), in particular for trawl doors. Schwinghamer et al. (1998) described the immediate impacts created by the trawl doors on the topography of the sediment surface in the Grand Banks of Newfoundland (Canada). The physical disturbance from trawling in a Scottish Sea Loch also showed strong evidence, with footprints on the seabed made by the trawl doors lasting 18 months after trawling (Tuck et al., 1998). Similarly in the Barents Sea, clear visible tracks and smaller depressions caused by trawl doors and the groundgear were recorded by video camera observations, although these disturbances had disappeared after five months (Humborstad et al., 2004). Some other investigations also provide evidence of physical disturbance, including trawl furrows and berms on the seabed or a general flattening of bottom features for instance ripples and irregular topography or even a reduction in bioturbation mounds and polychaete tubes caused by trawl gear components (e.g., trawl doors, wires, and groundgear) (Currie and Parry, 1996; Hall-Spencer et al., 1999; Sanchez et al., 2000; Smith et al., 2000). However, the physical impacts of bottom trawls are generally considered not uniform and depend on both the ecosystem (i.e., type of seabed, current, wave action, and biological activity) and how the fishing gear is designed and operated (Tuck et al., 1998; Smith, 2000; Humborstad et al., 2004; Rice, 2006, Valdemarsen et al., 2007). Therefore, the consequences of these effects for the benthic community structure are not well known in reality (Gislason, 1994).

1.2.3 Biological Impacts of Bottom Trawling

Past studies on the biological impacts of bottom trawling on benthic communities for both soft and hard bottom habitats have shown evidence of effects such as the decrease in abundance of sponges, corals and some long lived benthic species (see van Dolah et al., 1987; Rumohr and Krost, 1991; Bergman and Hup, 1992; Kaiser and Spencer, 1996; Watling and Norse, 1998; Prena et al., 1999; McConnaughey et al., 2000; Kenchington et al., 2001; Edinger et al., 2007). However, the results from several such investigations on this topic should be considered with caution. Most trawl impact studies conducted to date have focused mainly on the immediate effects of short-term trawling (on soft or sandy bottoms) and several of these investigations provide clear evidence of the short-term effects with considerable decreases in abundance of some individual taxa. For instance, Prena et al. (1999) conducted a comprehensive experiment on the impacts of bottom trawling on the Grand Bank of Newfoundland, demonstrating a 24 percent reduction in the total biomass of megabenthic species, while Kenchington et al. (2001) showed a 25 percent decrease in the total number of individuals (for the macrofauna, particularly polychaetes) immediately after trawling (on the Grand Bank), but likely recovered within a short period afterward. For the long-term effects of commercial trawling, only a few such studies have been conducted (due to the lack of appropriate control areas). Some of these studies have clearly shown that trawling results in reduced biomass of some benthic species such as erect sessile invertebrates, including sponges and corals (Engel and Kvitek, 1998 and McConnaughey et al., 2000). However, in some instances changes in biomass were more notable on control sites. Depending on the degree of seabed contact by the trawl gear components (i.e., groundgear, doors, and bridles) and habitat features, these effects can be significant (see van Dolah et al., 1987 and Moran and Stephenson, 2000).

In 2015, a noteworthy study published that bottom trawling had only a "negligible effect" on the seafloor and fish habitat in certain types of soft bottom (e.g., sand habitats) (Lindholm et al., 2015). The authors found that California's largely soft-bottom seafloor saw little lasting impacts with some smoothing of the seabed from trawling with a small-footgear (20.3-cm-diameter discs). There were also no significant differences between trawled and untrawled plots with respect to structure-forming invertebrates (e.g., sea whips) and mobile invertebrates (e.g., sea stars).

Coming from a different argument, Dutch scientists recently argued that there may actually be some unexpected benefits from bottom trawling (van Denderen et al., 2013). These surprising results were derived from modelling the effects of trawling on a simple ecosystem of benthivorous fish (flatfish species such as plaice and sole) and two food populations (benthos), susceptible and resistant to trawling. They demonstrated that the indirect-effects or side-effects of bottom trawling may result in higher fish abundance, and higher (maximum sustainable) yield or more productive in terms of food for fish that fishermen target. Such results will undoubtedly generate public and scientific debates, especially given evidence to date for other fisheries, coupled with a growing public ocean literacy and a need for long-term ocean sustainability.

1.2.4 Summary

The effects of mobile fishing gears (i.e., trawls and dredges) in general and bottom trawling in particular on the seabed and benthic communities have received increased attention over the last few decades. The potential impacts of bottom trawl fisheries have led to intense discussions and heated debates, both in academic/scientific forums and among many environmental NGOs, policy makers/fisheries managers, regulators, and the fishing industry. Based on the investigations of trawling impacts published to date, it can be said that the potential detrimental impacts of bottom trawling have been shown to be physical and biological. This includes the removal of major habitat features, reduction of structural biota and habitat complexity, changes in seabed structure and relative abundance of species, and increase in scavenger populations. However, these general statements should be taken into consideration and interpreted carefully before any relevant conclusions are made. Because the physical and biological impacts of trawling disturbances vary in the magnitude and longevity of effects under different habitat types and trawl gear designs, modeling assumptions related to impact studies or even the operational choices by fishermen (e.g., warp to depth ratio, towing speed). In fact, knowledge of how impacts of bottom trawling activities actually affect benthic communities is still limited and in many cases conclusions are ambiguous. The lack of such knowledge may be explained by the complexity of marine habitats, as well as the methodological limitations of measuring these effects. Marine benthic habitats are believed to provide shelter and refuge for juvenile fish and associated organisms comprising direct and indirect important food resources for demersal species. While the ecological consequences of bottom trawling impacts on benthic habitats and communities contain uncertainty for various reasons (regarding gear design and operation, natural disturbance regime, variations in substrate types, and biologic structure), the development of innovative trawling systems that are more environmentally friendly, selective, and efficient would be advisable.

1.3 Research and Development of Low-Impact Bottom Trawls

1.3.1 Background

Given environmental concerns, bottom trawling has been facing the challenges of increasing restrictions, area closures, as well as now being banned in many areas of the world. The United Nations, under the 2006 Sustainable Fisheries Resolution, called for closing certain areas to bottom contact fishing including seamounts, hydrothermal vents, cold water corals, and areas where vulnerable marine ecosystems existed (UNGA, 2007). To date, several countries such as Canada, Norway, Australia, and New Zealand have prohibited bottom trawling in some ecologically sensitive areas within their jurisdictions. The entire global seafood industry is facing public pressure to amend its fishing practices, particularly bottom trawling, in an effort to reduce bycatch and negative impacts on the seabed and benthic communities. In addition, current consumer trends and the growing demand for certification by eco-labels such as the Marine Stewardship Council indicate that the public is increasingly concerned with the environmental impacts of fishing, in particular, bottom trawling (Washington and Ababouch, 2011 and OECD, 2012). Therefore, the development of fishery-specific trawling systems that maybe considered more seabed friendly (i.e., low-impact trawl gears) has become a priority research agenda. Such research could lead to significant contributions to the reduction in seabed impact and the levels of bycatch while maintaining acceptable commercial catch rates compared to traditional fishing systems. Development and application of low-impact fishing gears is likely to contribute to sustainable fisheries and sustainable marine ecosystems. Low-impact fishing gears can promote stock productivity through a reduction of unaccounted fishing mortality and potential impacts on the seabed habitat and communities.

Many scientists have responded to the challenge of developing more environmentally friendly fishing gears with reduced seabed impacts. Along with the precautionary and ecosystem approaches to fisheries, recent literature has described, discussed, and proposed some mitigation measures to reduce the impact of mobile fishing gears on the seabed (see reviews by Valdemarsen et al., 2007 and He and Winger, 2010). These approaches were mainly suggested based on improving the fishing efficiency (e.g., increased catch rate to reduce bottom contact time/area) (Valdemarsen et al., 2007) or gear modifications by reducing contact area/weight and penetration of gear components (e.g., doors, sweeps, bridles, and groundgear) on the seabed (Rose et al., 2000, 2006; Ball et al., 2003; Munden, 2013; Murphy, 2014; Nguyen et al. 2015). In addition, the use of pelagic trawls and semi-pelagic trawls to target demersal species have also been developed to lessen seabed impacts and reduce bycatch levels (DeLouche and Legge, 2004; He et al., 2006; Sala et al., 2010; Rivierre et al., 2013). In some cases, there have been large EU funded projects (e.g., DEGREE) dedicated to measuring and addressing the topic of (van Marlen et al., 2010). While many of these initiatives have developed innovative technological solutions that reduce seabed impacts, the development of any one single 'perfect comprehensive solution' has not yet been achieved. Instead small scale discoveries and improvements has been more the norm. The result has been a slow evolution of small incremental changes in bottom trawl technology (Graham, 2006). No one would argue that bottom trawls are similar to those used 50 years ago. In fact they are dramatically different in many ways. But they are not perfect. For this reason, conservation engineering remains a hot discipline with many countries dedicated to the pursuit of more sustainable fishing practices.

1.3.2 Designing and Testing New Fishing Gears

Trawl designs and developments have become more advanced and sophisticated over the last few decades. This trend can largely be explained by the need for improvements in energy efficiency, species and size selectivity, reduced bycatch, and reduced impact on the seabed and benthic communities (Winger et al., 2006). In addition to this, the “methods” by which scientists and technologists design and test new developments has also been improving. This is attributed to the high cost of evaluating new gear designs at sea together with major advancements in computer aided simulation and physical modeling techniques, both of which have been shown to reduce relevant expenses and potential risks for gear manufacturers and researchers (Winger et al., 2006; Prat et al., 2008; Queirolo et al., 2009).

The methods by which a new fishing gear such as a bottom trawl is designed and evaluated have been refined for several decades with various theoretical and experimental methods (Tauti, 1934; Dickson, 1961; Fridman, 1973, 1986; Priour, 2013). Historically, these experiments were carried out using either 1) working engineering models in tow tanks or flume tanks, or 2) full-scale prototypes at sea. Given the cost of evaluating new trawl designs at sea, as well as the recent rise in commercially available simulation software, today’s gear designers, researchers, and manufacturers prefer to begin with computer simulation and the testing of physical scale models, before testing at-sea (see Figure 1.3 for the commonly used fishing gear development cycle). This allows designers to optimize proposed trawl concepts in a “low-cost” environment, rather than immediately preceding to sea with every new idea (Winger et al., 2006). The use of computer-based numerical modeling and simulation has significantly improved the speed and quality of design work, particularly during the early stages of design for validating simple design ideas (Ferro, 1988; Makarenko et al., 1998; Priour, 1999; Lee et al., 2005; Vincent and Roullot, 2006; Priour, 2013; Park et al., 2014). Parameters of interest typically include trawl geometry, mechanical stress on the seabed, and hydrodynamic drag or resistance (Vincent, 2000; Vincent and Roullot, 2006; Queirolo et al., 2009; Priour, 2013). With this step completed, refined trawl concepts can then be constructed in the form of scaled working engineering models. These models are then tested and evaluated using a flume tank (see Winger et al., 2006 for a list of available flume tanks worldwide). This is arguably the best approach for examining the effects of trawl rigging on hydrodynamic behaviour and performance, visually and in a direct way. This approach is also recommended for validating simulated values derived from previous numerical simulation work (Queirolo et al., 2009). Eventually, full-scale prototypes are constructed and evaluated under real fishing conditions for their mechanical performance and catchability. This often includes a wide assortment of underwater cameras and instrumentation in order to study animal behaviour and trawl performance *in situ*.

In ideal cases, the fishing gear development cycle finishes with trawl innovations being introduced into the fleet and implemented by industry (Figure 1.3). However, more often than not, the cycle is repeated in a repetitive manner until meaningful improvements are achieved. But is it that simple? Does developing and publishing new innovations necessarily affect change within the fishing industry? A recent article by Eayrs et al. (2014) highlights the fact that the fishing industry tends to be resistant to change. The authors argue that conditioning, conservatism, and uncertainty are possible reasons as to why new innovations often sit on the shelf and are not “taken-up” by industry. They suggest that lessons learned from the business community, in particular the theory of “change management” could be applied to the field of conservation engineering (i.e., fishing gear development). This is opening new insights into how fishing gear is developed and implemented into industry, and it may require a revision/improvement to the fishing gear development cycle (Figure 1.3).

1.4 Chapter Outlines

In Chapter 2, I study the behavioural interactions of individual snow crabs (*Chionoecetes opilio*) in response to the rockhopper footgear of a traditional inshore shrimp trawl used in Newfoundland and Labrador, Canada. The northern shrimp (*Pandalus borealis*) and snow crab fisheries are important contributors to the local economy of the province of Newfoundland and Labrador (DFA, 2015). The local fishing industry has been concerned about shrimp trawling as an important source of unaccounted mortality, negatively affecting the snow crab population and their habitat. Several attempts have been made to understand how shrimp trawling activities affect snow crab population and habitat in Canada (Schwinghamer et al., 1998; FDP, 2002; Gilkinson et al., 2006). Recent recommendations arose from the experiments conducted by Dawe et al. (2007), one of which was the need to conduct direct *in situ* video observations of snow crab interaction with trawl footgear. In this chapter, I record and evaluate individual snow crab interactions in response to different footgear components, including their orientation, reaction behaviour (i.e., direction of movement), and nature of encounter (i.e., different types of encounters, duration, and fate of encounter). I also discuss the impacts of shrimp trawling on the snow crab resource and recommend further research to better understand the interactions between snow crab and bottom trawls, as well as potential gear modifications to reduce impacts.

In Chapter 3, I conduct an overview of different commercially available trawl simulation software packages used to evaluate their design capabilities and predictive capability and reliability. Three major software packages were selected for the comparison, including: 1) DynamiT (developed by the French Research Institute for the Exploitation of the Sea-IFREMER, France), 2) SimuTrawl (developed by the Marine Production System Laboratory-MPSL, Korea), and 3) Trawl Vision PRO (developed by the AcruxSoft, Uruguay). First, I conduct a literature review including an overview of trawl simulation software and any scientific studies using the software. I then use the Campelen 1800 trawl (a Canadian demersal survey trawl) to evaluate the design/simulation capabilities of each software using various criteria (e.g., user-friendly, ability to self-training/using, modeling assistance, design capability, simulation capability and reliability). In addition, I also use at-sea data on the performance of the Campelen 1800 trawl to validate simulation results predicted by each software or to evaluate how each software replicates real-world performance. I discuss the strengths and limitations of each software and provide recommendations for the potential users.

In Chapter 4, I investigate how well computer simulation and flume tank testing of scale engineering models actually predict full-scale at-sea performance of bottom trawls. The use of computer simulation, physical modeling, and at-sea evaluations in a complementary manner and in a logical sequence of work is considered a major tenant of the fishing gear development cycle (Winger et al., 2006). In this chapter, I use a dynamic simulation software (DynamiT) to simulate the mechanical behaviour of the Campelen 1800 trawl under different working scenarios (e.g., differences in door spread, depths, and towing speeds). A 1:10 scale model of the Campelen trawl was then built and tested in a flume tank at the Fisheries and Marine Institute of Memorial University of Newfoundland (Canada) where the performance of the model was evaluated under different towing speeds and rigging arrangements. Then I use the data obtained from dynamic simulation and the flume tank to compare with the full-scale observations of the Campelen 1800 in action that were collected during the fall 2011 multi-species survey aboard the research vessel *CCGS Teleost*. I also use the numerical simulation data to compare against scale model engineering performance under identical conditions. I discuss the weaknesses and merits of each method and provide suggestions how to use them to support the gear development cycle.

In Chapter 5, I examine the effectiveness of a novel footgear for reducing the seabed impacts of shrimp trawls off the east coast of Newfoundland and Labrador, Canada. A “drop chain” footgear with reduced contact area was designed and tested using engineering models in a flume tank, as well as full-scale at-sea trials. I evaluate two experimental footgear designs, the 9-drop chain and 5-drop chain, in the Marine

Institute's flume tank to estimate contact area with the seabed. I also conduct two comparative commercial fishing experiments to examine catch rates of shrimp and bycatch, trawl geometry, fuel consumption, and trawling resistance between the traditional and experimental trawls (i.e., rockhopper footgear vs. drop chain footgear). In addition, I collect underwater video observations to determine the performance of the drop chain footgear relative to the seabed and its herding effects on shrimp and bycatch species, in particular the interaction or encounter of snow crab with the drop chains.

Finally, in Chapter 6 I provide an overall summary of the results and conclusions from each chapter. I discuss environmental concerns, gear research and development to reduce potential environmental impacts of northern shrimp trawling in Newfoundland and Labrador (Canada), as well as limitations of the approach and future research directions.

1.5 Co-Authorship Statement

I am the major intellectual contributor and principal author of all chapters presented in this thesis. This includes all practical aspects of the research, data analysis, interpretation, and manuscript preparation. However, my studies could not have been undertaken without the invaluable guidance and excellent supervision of my principle supervisor Dr. Paul Winger, great support and direction of my supervisory committee members Dr. Scott Grant (co-supervisor) and Dr. Robert Hooper, along with the collaborative contribution of many individuals. Their involvement is recognized here.

Chief collaborators for Chapter 2 were Paul Winger, George Legge, Earl Dawe, and Darrell Mullowney. Dr. Winger contributed substantially to the research proposal, experimental design, and discussion of ideas, as well as aided with the data interpretation and provided editorial reviews of the manuscript. Mr. Legge contributed to the experimental design and participated with the field work. Mr. Dawe and Mr. Mullowney provided input into the project design and provided editorial reviews of the manuscript. This chapter was published in the journal of Fisheries Research in 2014 (156:9-13).

Chief collaborator for Chapter 3 was Paul Winger. Dr. Winger contributed substantially to the research proposal, experimental design and discussion of ideas, as well as aided with the data interpretation and provided editorial reviews of the manuscript. This chapter was published in the journal of Fishery Technology for consideration of publication.

Chief collaborators for Chapter 4 were Paul Winger, Dave Orr, and George Legge, Harold DeLouche, and Alex Gardner. Dr. Winger contributed substantially to the research proposal, experimental design, and discussion of ideas, as well as aided with the data interpretation and provided editorial reviews of the manuscript. Mr. Orr participated with the field work and provided editorial reviews of the manuscript. Mr. Legge contributed significantly to the flume tank testing and aided with the data interpretation. Mr. DeLouche aided the design and construction of 1:10 scale model of the Campelen 1800 trawl and provided editorial reviews of the manuscript. Mr. Gardner participated with the field work. This chapter was published in the journal of Fisheries Research in 2015 (161:217-225).

Chief collaborators for Chapter 5 were Paul Winger, Philip Walsh, Brett Favaro, George Legge, Kelly Moret, and Scott Grant. Dr. Winger contributed substantially to the research proposal, experimental design, and discussion of ideas, as well as aided with the data interpretation and provided editorial reviews of the manuscript. Mr. Walsh contributed significantly to the research proposal, experimental design, participated with the flume tank testing and field work. Dr. Favaro contributed to the experimental design, participated with the field work, aided with the data interpretation, and provide comprehensive editorial reviews of the manuscript. Mr. Legge contributed to the experimental design, participated with the flume tank testing and field work. Mrs. Moret contributed substantially to the research proposal, experimental design, field work arrangement, and provided editorial reviews of the manuscript. Dr. Grant provided comprehensive editorial reviews of the manuscript. This chapter was published in the Journal of Ocean Technology in 2015 (2:61-77).

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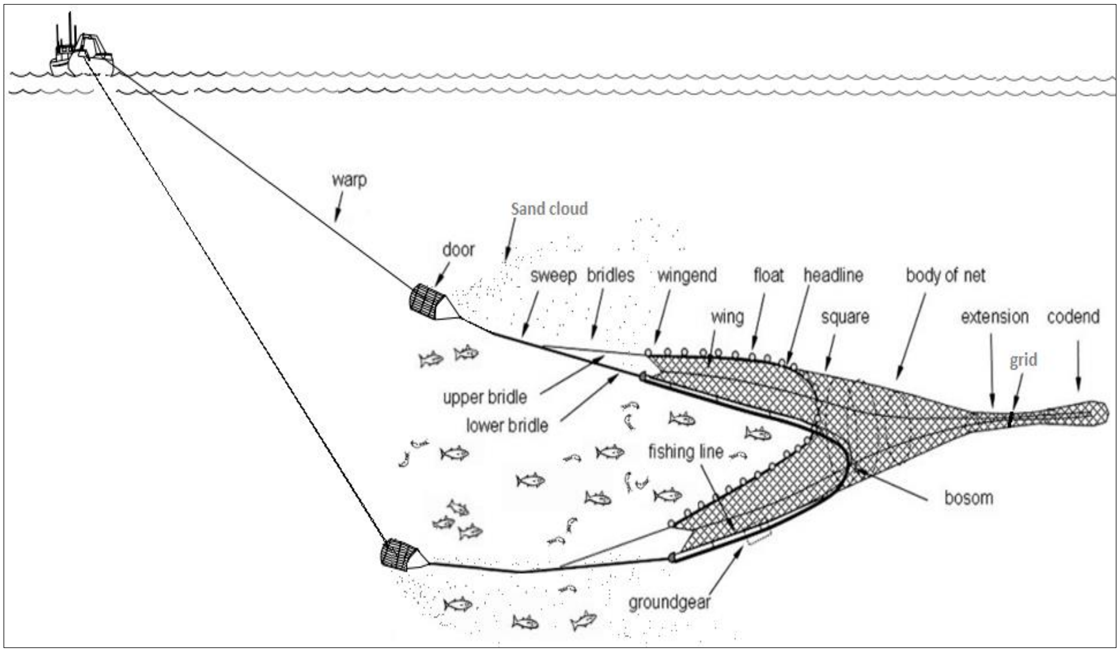

Figure 1.1: A schematic drawing of a bottom trawl in action (Adapted from He, 2007)

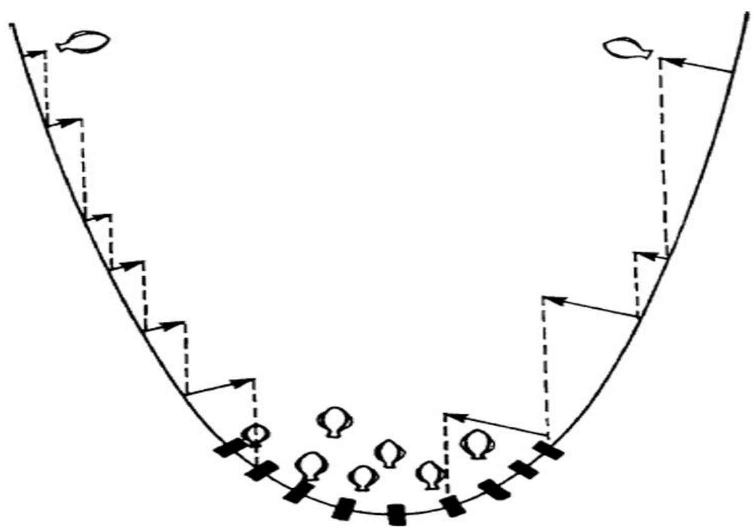

Figure 1.2: Demonstration of flatfish behaviour in the herding zone. They react to the sweeps/bottom bridles at a 90^0 degree angle, swimming away and settling again until they once again interact with the footgear (Winger et al., 2004).

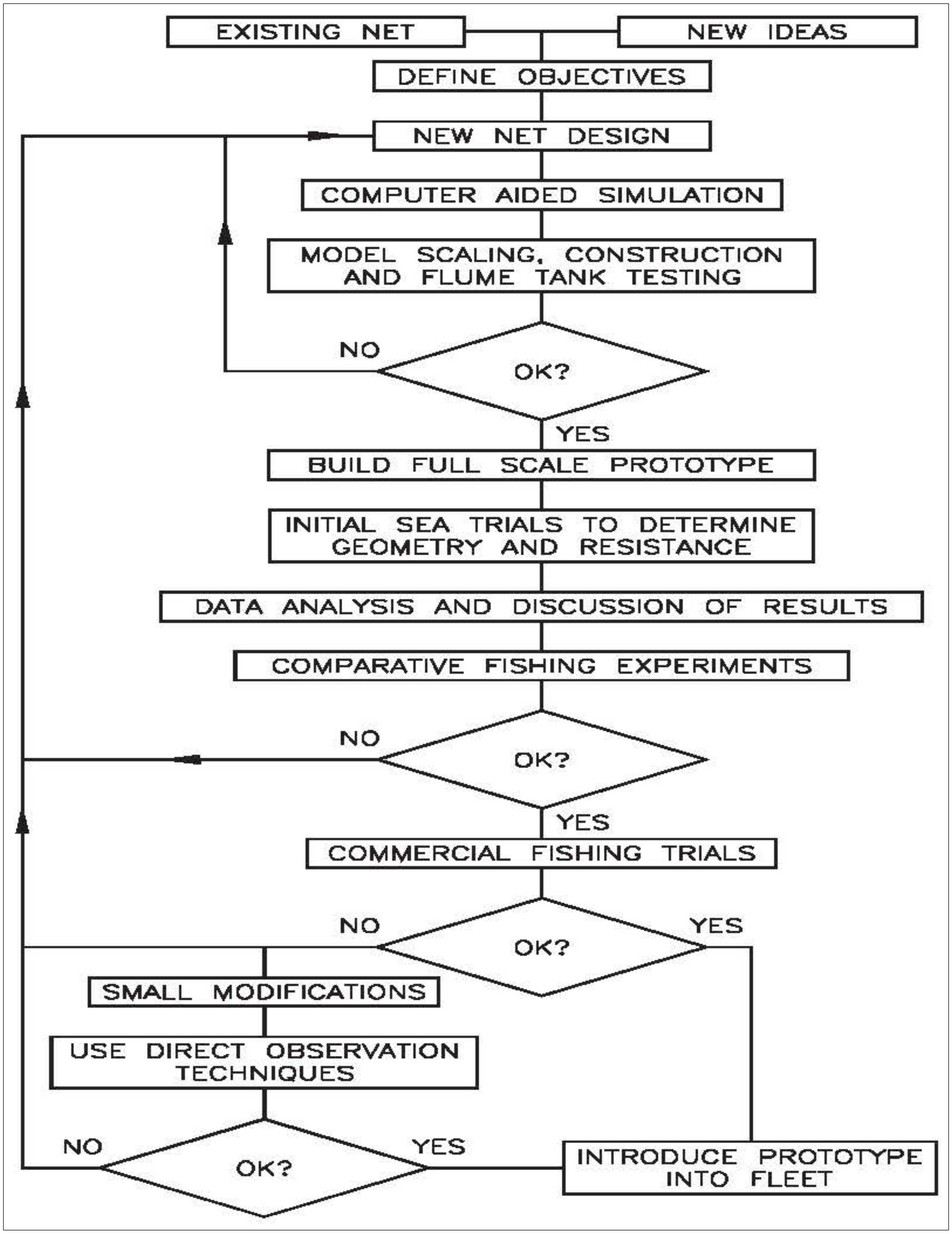

Figure 1.3: Fishing gear development cycle (Winger et al., 2006)

Chapter 2. Underwater observations of the behaviour of snow crab (*Chionoecetes opilio*) encountering a shrimp trawl off northeast Newfoundland

2.1 Abstract

Trawl-mounted video camera observations were conducted to understand how individual snow crab (*Chionoecetes opilio*) interact with the rockhopper footgear components of a traditional inshore shrimp trawl used in Newfoundland and Labrador, Canada. Observations of individual snow crab interactions with different footgear components were recorded and evaluated including their orientation, reaction behaviour (i.e., direction of movement), and nature of encounter (i.e., different types of encounters; duration of encounter, and fate of encounter). The analysis demonstrated that snow crabs were quickly overtaken by the approaching trawl and about 54% of the crabs observed were confirmed to experience an encounter with the footgear (either disc or spacer/chain). The study also revealed that the majority of the crabs observed appeared to be aware of the trawl and appeared to be actively responding and/or reacting to the approaching threat. I discuss the impacts of shrimp trawling on the snow crab resource, further research required to better understand the interactions between snow crab and bottom trawls, as well as potential gear modifications to reduce impacts.

2.2 Introduction

The Newfoundland and Labrador snow crab (*Chionoecetes opilio*) fishery is the province's highest value fishery, one of Canada's most valuable fisheries, and has achieved Marine Stewardship Council (MSC) certification. The importance of the snow crab fishery to the economy of Atlantic Canada has increased significantly since the collapse of the Northern cod and other groundfish resources on the Canadian East coast in the early 1990s. The snow crab fishery in the province of Newfoundland and Labrador grew steadily since 1990s and currently has approximately 3,200 license holders under fishing enterprise allocation and annual landings of over 50,000 tonnes (Mullowney et al., 2012a and DFA, 2013). However, there are recent indicators of a resource decline in some areas, particularly in northern regions (e.g., NAFO Divisions 2HJ3K). Survey and fishery catch rates have decreased in each of these divisions in recent years (Mullowney et al., 2012a). Stakeholder members are deeply concerned about the situation and suspect multiple potential contributing factors, including poor recruitment, changing environmental conditions, increased predation, and interaction with the mobile gear sector (e.g., bottom trawling). Fisheries and Oceans Canada (DFO) has recently proposed and implemented new management measures to conserve and protect the snow crab resource, including reductions in total allowable catch (TAC), soft-shelled crab protocols to protect pre-recruit crabs, biodegradable twine to limit ghost fishing, voluntary gear modifications to improve selectivity, and closed areas (e.g., Winger and Walsh, 2011 and Mullowney et al., 2012a,b).

One of the primary concerns raised by industry is their contention that shrimp trawling represents an important source of unaccounted mortality, negatively affecting the snow crab population and habitat. Several recommendations arose from the experiments conducted by Dawe et al. (2007), one of which was the need to conduct direct in situ video observations of snow crab interaction with trawl footgear. Such work was not immediately conducted, however recent indicators of poor stock health in NAFO Division 3K renewed interest in this area of research. The objective of this study was to provide behavioural insights into how individual crabs react to trawls by conducting trawl-mounted video observations of the interaction.

2.3 Materials and Methods

2.3.1 Study Area

The experiment was conducted in NAFO Division 3K on the northeast coast of Newfoundland, Canada with average water depths ranging from 373 to 393 m. More specifically, this area was chosen because the shrimp and crab fisheries are known to overlap in this location and were recently closed to crab fishing due to a high incidence (>20%) of soft-shelled crab. Choosing an area recently closed as a result of the soft-shelled-protocol was not only expected to ensure the presence of soft-shelled snow crab but also absence of crab gear, facilitating the trawling experiment without the issue of gear conflicts.

2.3.2 Camera System and Operation

A self-contained low-light underwater camera system owned by the Fisheries and Marine Institute of Memorial University was used for the experiment. The equipment, developed by JT Electric (Faroe Islands), was attached to the headrope and footgear of a traditional inshore shrimp trawl to collect close-up video footage of crab interactions with trawl footgear.

2.3.3 Field Observations

The experiment was carried-out onboard the commercial vessel Lynette Marie II on the northeast coast of Newfoundland in late June 2012. The vessel, registered in the province of Newfoundland and Labrador as part of the shrimp fleet in NAFO Division 3K, was equipped with a traditional shrimp trawl with rockhopper footgear. The trawl was rigged with a 28.2 m rockhopper footgear comprised of 356 mm diameter rubber discs with a minimum spacing of 179 mm between the discs (Figure 2.1). Netting in the trawl consisted of 6.0, 4.0 and 1.8 mm diameter polyethylene twine varying in mesh size from 80-100 mm in the wings, the square and 50 mm in the bellies, extension, and codded.

A camera unit was mounted directly to the fishing line at the centre of the footgear, close to the seabed (i.e., 0.6-1m). A lighting unit was also attached to the headline of the trawl aimed downward to illuminate the field of observation to improve the quality of video. Altogether, 15 tows were conducted resulting in five successful tows (Tow 11-Tow 15) yielding a total of 9.5 hours of usable video for detailed analysis.

2.3.4 Data Analysis

Analysis of the video footage was conducted using AVS video editor software on a high definition monitor in order to measure specific objective parameters for individual crabs in response to the approaching rockhopper footgear components (i.e., disc, spacer/chain).

The parameters measured included the numbers of snow crab observed, the position of each crab relative to the substrate (i.e., either on the surface or in the mud), the orientation and movement of each crab (i.e., walking, not walking, or unknown), the direction of movement, and nature of the encounter (i.e., type of encounter, duration of encounter, and fate of encounter). We assumed that crabs perceive an approaching bottom trawl in the same way that fish perceive an approaching bottom trawl. In making this assumption, we were able to build upon established predator–prey theory for animal-trawl interactions (e.g., Ryer, 2008 and Winger et al., 2010). In particular, we assume that a crab under the threat of an approaching trawl will continually choose between two behavioural options, staying where it is (and perhaps continuing with an ongoing activity) or fleeing, as the distance between it and the trawl shrinks.

The nature of each crab's interaction with footgear components (i.e., discs, spacers, travel chain) was also investigated. We categorized each crab as either; a) experiencing a direct encounter with the disc, b) experiencing an encounter with the spacer/travel chain, c) passing between the discs with no apparent encounter, or d) unknown because either the crab or the footgear left the field of view and the actual interaction could not be determined.

The orientation and direction of movement of each crab relative to the direction of tow and the centre of the footgear were measured manually using a transparent protractor over-laid on the video monitor. The crab's eyes were used to determine its orientation (e.g., a crab facing toward the approaching footgear was given a value of 180 degrees, whereas a crab facing the tow direction was assigned 0 degrees). The Raleigh statistical test using Oriana version 4.01 was used to test whether these parameters (orientation and direction of movement) were randomly distributed.

2.4 Results

A total of 1081 crabs were observed. The majority (93%) were on the surface of the substrate while 7% were in the mud. The numbers of crabs were found to be different between tows, depending on the quality of video. Other factors such as crab density and patchiness of the seabed substrate may have also played a role.

The majority (87%) of the crabs observed were walking while 12% of crabs were categorized as not walking, and the remaining 1% were unknown.

Of the crab observed, a total of 54% experienced an encounter with the footgear (either disc or spacer/chain), while 25% had no encounter (i.e., went between the discs), and 21% went outside the field of view (Figure 2.2). The vast majority of encounters were less than 1s in duration (approximately 90%), while approximately 8% were between 1 and 10s, and the remaining 2% were longer than 10s. Only in very rare cases was excessively long impingement (i.e., snagging) observed, with the longest impingement lasting approximately 6 minutes. For crabs involved in an encounter (n = 583), 95% went under the footgear while 5% went over the footgear.

The orientation of the crabs on or in the substrate relative to the centre of the footgear and direction of the tow was non-random ($p < 0.001$) (Table 2.1). The majority of crabs were oriented in the range of 75 deg. through 285 deg., with a mean of 193°deg (Figure 2.3). Very few individuals were oriented in a direction facing away from the approaching trawl, suggesting they appeared to be aware of the approaching threat.

For individuals categorized as moving, the direction of movement relative to the centre of the footgear and towing direction was non-random ($p < 0.001$) (Table 2.1). The majority of crabs were moving in directions ranging from 270 deg. through 90 deg., with a mean of 1.9° deg. (Figure 2.4). Very few individuals were moving toward the approaching trawl, suggesting they were appeared to be actively avoiding the approaching threat.

2.5 Discussion

The results of this study suggest an effect of shrimp trawling on snow crab mortality, with approximately 54% of the crab observed were confirmed to experience a direct encounter with the footgear components. However it is important to note that we were unable to investigate the severity, degree of pain, or likelihood of mortality after passing under the footgear. Furthermore, our observations focused only on the center of the footgear thus limiting our ability to evaluate interactions in other regions of the trawl.

One of our major findings is that the majority of the snow crabs appeared to be aware of the approaching trawl and most were actively responding and/or reacting to the approaching threat (e.g., footgear components). This finding is consistent with Rose (1995) who documented Alaskan red king crab "running away" from approaching ground gear components. Similar to red king crab, snow crab in our study showed limited ability to avoid approaching trawls and were quickly overtaken, resulting in unintended encounters. These reaction behaviours remain poorly understood, but could be viewed against a backdrop of related studies investigating fish reactions to trawls. Recent literature suggests that fish respond to bottom trawls in a manner consistent with predator-prey theory, with the trawl constituting the predator (e.g., Ryer, 2008; Winger et al., 2010; Underwood et al., 2012). If we assume this to be true for crabs, then it is logical to assert that individuals make behavioural tradeoffs that minimize risks and maximize benefits consistent with the economic or adaptive risk-assessment hypothesis (Ydenberg and Dill, 1986). In the case of vertebrate fish, hundreds of studies have been conducted since the 1960s to investigate the various intrinsic and extrinsic factors that affect fish behaviour in response to approaching trawls (see review by Winger et al., 2010). Factors known to modify fish behaviour include: underwater light field (light level, contrast, and colour), water temperature, animal density, animal size, motivational state, physiological condition, learning and experience. The current experiment was not designed to investigate such effects, but does draw attention to the gulf of knowledge when comparing these two phyla.

Our observation that the majority of crabs were actively reacting to the trawl suggests that the individuals we observed were of hard-shelled condition. Though shell condition could not be determined from the video, we speculate that the crabs must have been of hard-shelled condition in order to demonstrate the behaviour observed. We suggest that truly soft- shelled individuals would probably be unlikely to actively respond to the trawl and could therefore be more susceptible to mortality or damage. Although further research is required to validate this hypothesis, in a precautionary measure, DFO extended the soft-shell protocol in NAFO Division 3K in 2013 to prohibit trawling (along with trap fishing) for the duration of the crab fishery in grids that were closed due to a high incidence of soft-shelled crab. In 2002, DFO established the 1,370 km^2 Hawke Box exclusion zone which was expanded to 8,610 km^2 in 2003. The Hawke Box is located off Southern Labrador in NAFO Subarea 2J (i.e., shrimp SFA 6). The Hawke Box was closed to shrimp trawling and groundfish fisheries in response to concerns that they were negatively affecting Atlantic cod and snow crab populations and habitat. Only trap fishing for snow crab is permitted inside the exclusion zone. A recent study demonstrated that the Hawke Box exclusion zone failed to protect pre-recruit crabs largely due to a redistribution and intensification of directed snow crab effort inside the Box in years following the closure (Mullowney et al., 2012b). A similar trawling closure (Funk Island Deep Closure) was established in offshore Division 3K in 2005 and similar to the Hawke Box, there is currently no evidence to suggest it has had any positive impacts on snow crab resource status, with fishery catch rates declining more inside the closed area than outside in recent years (Mullowney et al., 2012a).

The ability to detect individual crabs relative to the rockhopper footgear components was limited by murky water and low light penetration. This limitation is known as one of the common technological challenges when conducting species-specific behavioural observations in dynamic underwater environments (e.g., Hemmings, 1973; Graham et al. 2004; Underwood et al., 2012). Some particular consequences are that only a small portion of the area swept during trawling could be monitored, we were not able to determine the reaction distance of the crabs, and we were unable to determine size, shell condition, or sex of the crab.

Artificial light is well known to modify animal behaviour as it alters the underwater light field (i.e., light level, colour, and contrast). Its effect on fish reactions toward fishing gear has been well documented (Glass and Wardle, 1989; Walsh and Hickey, 1993; Engås et al., 1998; Olla and Davis et al., 2000). However, in this study we could not investigate snow crab response to the footgear components without the use of artificial (white) light due to the significant depth of the snow crab distribution. We recognize this was a limitation of our experiment and that the light may have altered crab behaviour and biased our results. Hence we suggest the results be interpreted with caution and recommend future research develop methods to observe the behaviour of snow crab without the use of white light.

To better understand whether shrimp trawling negatively affects snow crab population and habitat, underwater observations of interactions between individual crabs and other components of the trawl (e.g., sweeps/bridle and wing-sections of the footgear) should be conducted. Rose et al. (2013) reported differential mortality rates depending on the component of the trawl encountered, with significantly higher mortality in the wing-sections of a trawl footgear relative to the centre. Such component-specific mortality should be further clarified and scientifically documented in order to help gear technologists and scientists develop less damaging footgear/sweeps to reduce crab encounters and potential mortality while sustaining capture rates of target species. Conducting trawl modifications (e.g., less- and/or non-bottom contact trawl doors/sweeps/bridles/footgear) is considered a potential approach to minimize encounters of snow crab with different bottom contact components of the trawl. For example, by raising the sweeps off the bottom, Rose et al. (2013) verified that such modification can help to reduce unobserved mortality of red king crab from 10% to 4%.

In conclusion, this study revealed that the majority of snow crabs observed were aware of the footgear and were actively responding to the approaching threat. Crabs were quickly overtaken by the approaching footgear and generally unable to avoid an interaction. Approximately 54% of the crabs observed were confirmed to experience a direct encounter with the footgear, suggesting an effect of trawling on damage or mortality to snow crab. While the extent of this impact remains unquantified, the behavioural knowledge gained from this study should assist stakeholders toward the development of trawling systems with reduced impact.

2.6 Acknowledgments

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Table 2.1: Basic statistical summary and Rayleigh test for the orientation and direction of movement of snow crab on or in the substrate relative to the centre of the footgear and tow direction.

Variable		
Orientation		
	Number of observations	1081
	Mean vector (µ)	193.°
	Length of mean vector (r)	0.207
	Median	190.0°
	Concentration	0.423
	Circular variance	0.793
	Circular standard deviation	101.8°
	95% confidence interval (-/+) for µ	181.5°-204.6°
	Rayleigh Test (Z)	46.253
	Rayleigh Test (p)	**< 0.001**
Direction of movement		
	Number of observations	938
	Mean vector (µ)	1.9°
	Length of mean vector (r)	0.655
	Median	0.0°
	Concentration	1.759
	Circular variance	0.345
	Circular standard deviation	52.7°
	95% confidence interval (-/+) for µ	358.4°-5.3°
	Rayleigh Test (Z)	402.987
	Rayleigh Test (p)	**< 0.001**

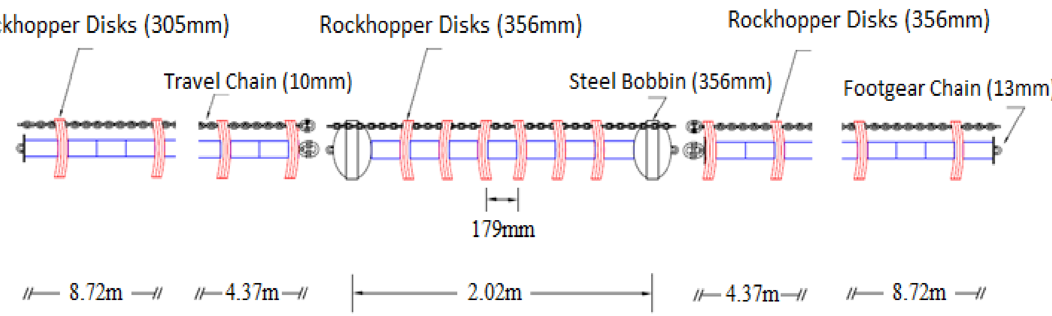

Figure 2.1: Schematic drawing of a traditional rockhopper footgear used in the study

Figure 2.2: Example images showing different types of encounter. (a) the crab got stuck into the disc; (b) the crab was snagged into the spacer/chain; (c) the crab went under the disc.

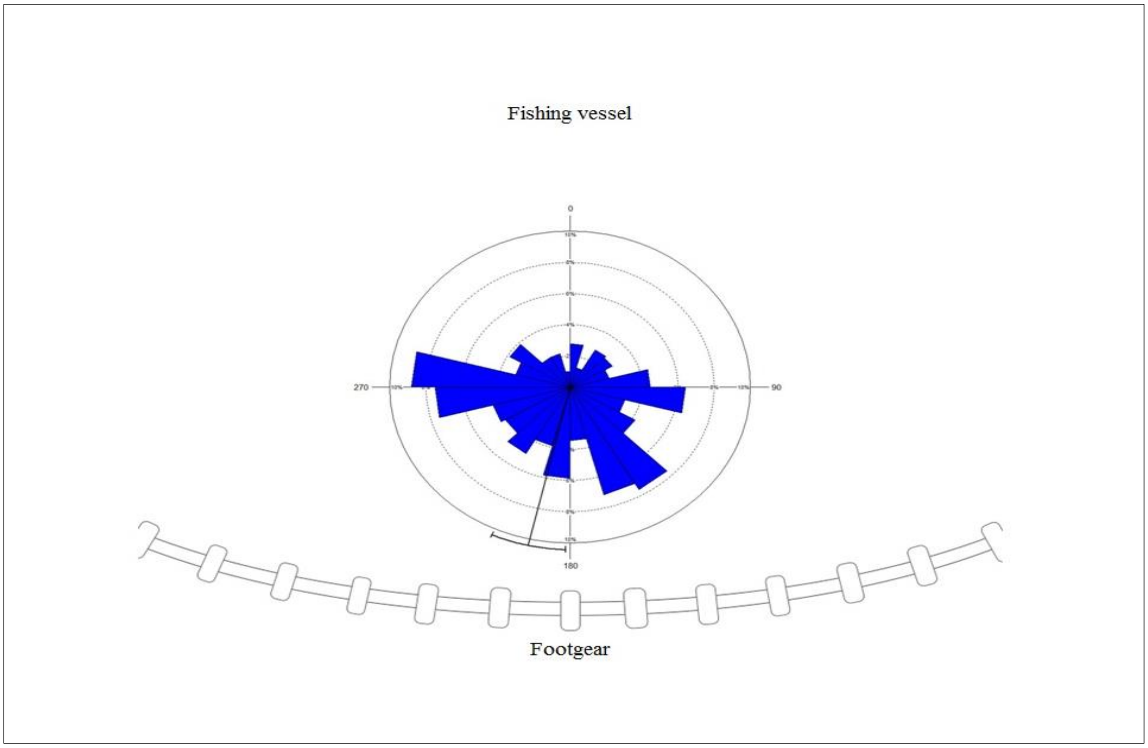

Figure 2.3: The orientation of the crab on or in the substrate relative to the centre of the footgear and the direction of tow. The blue bars indicate percentage of individuals. The black line indicates the mean direction (193°) and the bar at the end indicates 95

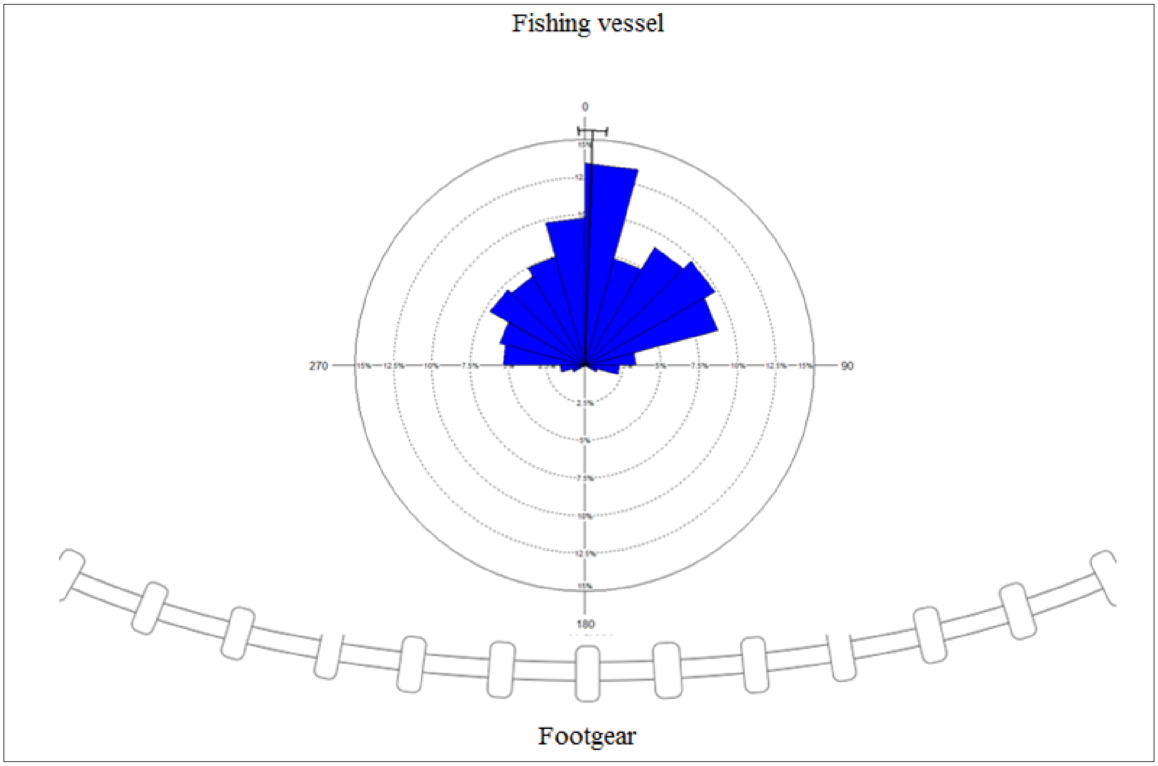

Figure 2.4: The direction of snow crab movement on the substrate relative to the centre of the footgear and towing direction. The blue bars indicate percentage of individuals. The black line indicates the mean direction (1.9°) and the bar at the end indicates 95%.

Chapter 3. Numerical modeling method for simulating bottom trawls

3.1 Abstract

Numerical modeling and simulation has emerged as a new and powerful tool for understanding the dynamic behaviour of bottom trawls. Based on hydrodynamic theory and principles, a bottom trawl can now be mathematically modeled in order to predict its dynamic performance under different conditions. An increasing demand for the use of computer-based numerical modeling is reflected by the recent rise in trawl simulation software commercially available in the market, allowing users to conceptualize trawl designs and evaluate their performance from the comfort of a desktop computer. In this study, I present an objective evaluation of three widely used trawl simulation software packages: DynamiT, SimuTrawl, and Trawl Vision PRO. The Campelen 1800 (a Canadian demersal survey trawl) was used to examine strengths and limitations of each software including the ability in predicting downward forces of gear components on the seabed, and to compare different design and simulation capabilities. The precision and accuracy of the simulation predictions was also validated using the full-scale at sea observations of the Campelen 1800 trawl which were collected during the 2011 fall multi-species survey aboard the research vessel *CCGS Teleost*. The study demonstrates that each of the software packages have their own weakness and merits in terms of design and simulation capability and reliability of the predictions. Numerical modeling is essential for understanding and predicting the dynamic behavioural performance of

bottom trawls and should be used as complementary tool in addition to physical modeling method and full-scale experiments.

3.2 Introduction

The development of fishing gears for the commercial fishing industry has changed dramatically over the last few decades as a result of increasing regulations, the need for species- and size-selectivity, stringent bycatch restrictions, as well as the necessity to reduce fuel consumption and minimize ecosystem impacts. Bottom trawls used for commercial and scientific purposes have become increasingly complex in their design, material choice, and construction. Understanding the dynamic behaviour and performance of these flexible structures prior to expensive sea trials is a key step in the fishing gear development cycle (Winger et al., 2006). Numerical modeling, in particular, is becoming one of the popular methods of evaluating trawl designs and assessing their performance during the early stages of gear development (e.g., Fiorentini et al., 2004; Lee et al., 2008; Queirolo et al., 2009; Nguyen et al., 2015).

Studies on the dynamic behaviour and performance of mobile fishing gear systems (e.g., bottom trawls) have been investigated for several decades using various theoretical and experimental methods (e.g., Tauti, 1934; Dickson, 1961; Fridman, 1973, 1986). Historically, these experiments were carried out using either 1) working engineering models in tow or flume tanks, or 2) full-scale prototypes at sea. However during the last two decades, numerical modeling and simulation has emerged as a new and powerful tool for understanding the dynamic behaviour of mobile fishing gear systems. Based on hydrodynamic theory and principles, a fishing gear system can now be mathematically modeled in order to predict its dynamic performance under the influence of various forces in the aquatic environment (e.g., external forces such as drag force, shearing force, sinking force, and buoyancy) and the properties of the materials used (e.g., elasticity and stiffness of twines). Numerical modeling of fishing gear systems has improved substantially in recent years given major advancements in mathematical theory, numerical simulation methods, and the computational power of modern desktop computers (Bessonneau and Marichal, 1998; Lee and Cha, 2002; Lee et al., 2005, 2008; Zhang et al., 2011; Priour, 2013; Li et al., 2015). An increasing demand for the use of computer-based numerical modeling is reflected by the recent rise in trawl simulation software commercially available in the market. With regard to bottom trawls, the market currently offers several trawl simulation software packages (e.g., DynamiT, Trawl Vision PRO, SimuTrawl, NETSIM simulator, and CATS II), allowing users to conceptualize trawl designs and evaluate their performance from the comfort of a desktop computer. The most common application has been the optimization of gear performance, including shape, geometry, drag, and seabed impact (e.g., Makarenko et al., 1998; Priour, 1999, 2013; Freiria, 2012; Lee et al., 2005, 2008; Vincent and Roullot, 2006; Park et al., 2014; Nguyen et al., 2015). Today, many gear designers, researchers, and manufacturers prefer to begin with numerical modeling of early conceptual ideas, followed by physical testing of scale engineering models in a flume tank (Winger et al., 2006). Eventually, full-scale prototypes are constructed and evaluated under real fishing conditions for their mechanical performance and catchability. While numerical and physical modeling have their respective advantages and limitations (Priour, 2013), both have been shown to be complimentary tools in predicting full-scale trawl performance (Nguyen et al., 2015).

This study provides a review and evaluation of three commercially available trawl simulation software packages including: 1) DynamiT (version 2.1), developed and distributed by the French Research Institute for the Exploitation of the Sea (IFREMER), France; 2) SimuTrawl (version 14.0425 for the Design program and version 1.0331 for the Simulation program), developed and distributed by the Marine Production System Laboratory (MPSL), Korea; and 3) Trawl Vision PRO (version 1.2.8 for the Trawl Vision Designer-TVD and version 1.6.3 for the Trawl Vision Simulator-TVS), developed by AcruxSoft, Uruguay. These particular software packages were selected for evaluation as they are widely recognized by gear designers, net makers, researchers, and fishing industry. Most of these software packages have the ability to simulate the mechanical behaviour and effects of different materials and design features on trawl configuration and performance under different rigging and towing scenarios (e.g., Vincent, 1999; Freiria, 2012; Queirolo et al., 2009; Nguyen et al., 2015). The software can also be used to study how trawl gears impact the seabed or how a trawl can be modified in order to reduce the fuel consumption (van Marlen et al., 2010). Other simulation software such as the NETSIM simulator-real-time 3D simulation for the trawl fishing gear (Park et al., 2014), and CATS II as an updated version of SINTEFs program (i.e., CadTrawl and CATS) for simulation of trawl performance (Hansen and Madsen, 2012), were not evaluated in this study as they were not considered fully commercialized products or not widely recognized by trawl designers and net makers. Our study was not conducted to determine which trawl simulation software is "the best one", but rather to identify strengths and limitations of each software, and to compare different features and functions regarding their capabilities and reliabilities. This study provides valuable knowledge for fishing companies, trawl designers, net makers, researchers, and educators who are considering purchasing software for numerical modeling and simulation.

The following sections provide an overview and description of the three trawl simulation software packages used in this study (i.e., DynamiT, SimuTrawl, and Trawl Vision PRO). Much of this information is sourced from literature and manuals written and distributed by developers of the software, as well as scientific literature.

- ***DynamiT***

DynamiT is a comprehensive trawl simulation software developed by IFREMER to perform dynamic trawl simulation in order to provide information related to geometry and forces. The simulation software uses a series of mechanical equations (structural and hydrodynamic) to characterize the shape and performance of a bottom trawl (Vincent and Roullot, 2006). This involves solving several equilibrium equations at the same time (e.g., equations of the dynamic mechanic balance, equations taking into account the elasticity of the bar, and equations describing hydrodynamic forces and other external forces due to water current). Each twine of the net is modeled by two rigid bars or more, to model the elasticity and rigidity of the twine. The bars are linked together with perfect knee joints (Vincent, 1999). The major strengths of the software lie in its ability to take into account a number of parameters and elements of an actual trawling system. A number of design and simulation capabilities of DynamiT has described by Vincent (1999).

DynamiT is considered one of the most well-documented simulation tools available. There are several examples in the scientific literature of applications of DynamiT. An introduction to DynamiT and its applications was presented by Vincent (1999). Vincent and Roullot (2006) demonstrated a series of examples of DynamiT applications to reduce the hydrodynamic drag (up to 30% in towing tension) of different trawl types (e.g., shrimp trawls, Cephalopod or squid trawls, twin-trawls, and pair trawls) with the goal of reducing fuel consumption. Queirolo et al. (2009) used the software to conduct numerical simulation of a new trawl design for Chilean crustacean fisheries. The software was also used to evaluate the mechanical impact of novel "seabed-friendly" trawl door concepts (see van Marlen et al., 2010). More recently, Nguyen et al. (2015) used the DynamiT software to assess the accuracy of numerical modeling and physical modeling approaches in predicting the full-scale at-sea performance (geometry and resistance) of the Campelen 1800 survey trawl. The authors also investigated the ability of the DynamiT to predict the performance of physical models in a flume tank.

- ***SimuTrawl***

SimuTrawl is a comprehensive numerical and simulation software package that includes two separate programs: trawl gear design and simulation. It simulates most types of commercially important trawl types, including mid-water trawls, bottom trawls, multirig trawls, pair trawls, and Danish seines. Similar to DynamiT, SimuTrawl provides a tool to predict the engineering performance of a proposed trawl design. It also has the ability to predict estimated mechanical forces of gear components (e.g., trawl doors and footgear) on the seabed. The depth of seabed, the speed and direction of both wind and currents can be set for any fishing environment. The simulation program is also used for 3D visualization of the fishing system for the purpose of checking the shape and the performance of the trawl. SimuTrawl is developed based on the application of a physically based mass-spring model (Lee, 2002; Lee and Cha, 2002; Lee et al., 2005). This model expresses the constituents of a virtual fishing gear system as mass points (i.e., the knots of its mesh are considered as mass points) having mass and mass-less springs (i.e., the bars of its mesh are considered as a spring without mass) connecting these points. In the case of trawls, the knots and bars of netting are transformed into knots and massless bars of virtual mesh (e.g., a small mesh trawl net may have several thousand of meshes) as mass points of a mathematical model. All the external forces such as drag, sheering force, sinking force, and buoyancy which work on the element are centered only on the mass points.

There are several examples in the scientific literature describing the development and application of SimuTrawl. Lee and Lee (2000), Lee and Cha (2002), and Lee et al. (2005) described a physical modeling method (i.e., a physical based mass-spring model) which was used to develop the SimuTrawl. The authors demonstrated that the simulated results qualitatively agree with the field experiments (Lee and Cha, 2002 and Lee et al., 2005). The software also permits the prediction of the shape and motion of the gear in accordance with changes in operation and gear designing parameters (Lee et al., 2005). More recently, the software has been used to estimate and accurately predict the swept volume of survey trawls (Lee et al., 2011). In that study, generalized modeling methods were developed and described for simulating the shape and movement of the gear. The authors then applied this model to simulate and calculate trawl shapes and their corresponding swept volume in relation to different towing speeds.

- ***Trawl Vision PRO***

Trawl Vision PRO is a new and rapidly growing simulation software developed and distributed by AcruxSoft, Uruguay. The software package includes two different programs: Trawl Vision Designer (TVD) and Trawl Vision Simulator (TVS). The TVD is a trawl design tool which allows the user to create their own trawl designs with a very user friendly interface based on existing net design templates (more than 150 available predefined templates). The Trawl Vision Simulator allows the user to create 3D visualizations using an extremely user friendly interface in which the dynamic behaviour of trawl designs can be viewed under various rigging, towing speed, and depth scenarios (AcruxSoft, 2012a). In addition to the design and simulation programs (i.e., TVD and TVS), AcruxSoft has developed and recently commercialized a trawl monitoring software, called Trawl Vision Instrumentation (TVI). This third program is designed to be installed on fishing vessels and integrated with any SIMRAD trawl monitoring system for simulating the real-time behaviour of the trawling system, including the catch performance (Mayans, 2011). Trawl Vision PRO is developed based on the application of a number of mathematical models which were proposed by Fridman (1969, 1986), Nomura and Yamazaki (1975), Wileman and Hansen (1988), and Ferro and Hou (1984), in order to predict the geometric configuration and forces of a bottom trawl (Freiria, 2012). Mathematical models are considered for the major elements and components of a bottom trawl, including doors, floats, cables, and the trawl net itself (Freiria, 2012).

The very first version of Trawl Vision, named AcruxSoft 2.0, was developed and initiated in 1989 by Frank Chalkling (F. Chalkling, AcruxSoft, pers. comm.). More recently, Freiria (2012) described a numerical model with mathematical procedures which were used to calculate the resistance of the different components of a trawling gear, by deduction of the drag and lift components. The author also demonstrated a comparison between the simulation results predicted by the Trawl Vision software and at-sea data provided by vessel-owners. The comparison revealed small differences (2.5 to 4.5%) for the distance between doors, while larger differences were observed in the vertical opening of the trawl mouth (up to 20%). Although little scientific literature on the development and application of the software is available, Trawl Vision PRO is widely used as a tutorial for students learning about fishing gears, gear demonstration, and training for fishermen. Trawl Vision PRO also targets trawl manufacturers and researchers who want to improve the existing gears and design new gears (AcruxSoft, 2012b).

3.4 Materials and Methods

3.4.1 Trawl Design Identification

The Campelen 1800 was selected as the trawl design for this study. This is the standard demersal survey trawl widely used by Fisheries and Oceans Canada on the east coast of Canada since 1995, replacing earlier versions of the Engel 145 otter trawl and the Yankee 41 shrimp trawl (Walsh and McCallum, 1997). This trawl design is known as a four panel design with cut-away lower wings and is rigged with three bridles and 4.3 m^2, 1,400.0 kg Morgère Polyvalent trawl doors. The Campelen 1800 trawl is rigged with a 35.6 m rockhopper footgear and uses 356 mm diameter rubber disks. Trawl construction consists of 4.0, 3.0 and 2.0 mm diameter polyethylene twine varying in mesh size from 80.0 mm in the wings to 60.0 mm in the square and the first bellies and 44.0 mm in the remaining bellies, extension, and codend (Figure 3.1). The design has changed very little over time as a result of stringent standardization of construction and operational protocols (Walsh et al., 2009).

3.4.2 Data Requirements

Prior to simulation, each software required input data for a number of parameters which were used to define the Campelen 1800 trawl. This included:

- Data related to all the netting panels;
- Data related to the strengthening ropes;
- Data related to the floatation;
- Data related to the footgear or footrope

- Data related to the riggings;
- Data related to the doors;
- Data related to the vessel;
- Data related to the seams (e.g., assembling the netting panels together, connecting the trawl net to the strengthening ropes and wires).

3.3.2 Design and Simulation Capabilities

The capability of each software package was evaluated using a number of criteria (see Table 3.4). This included the ability of the software to describe a variety of complex trawl designs (e.g., complicated riggings and multiple wingtips) and simulate these trawls under different fishing conditions (e.g., towing in a deep water or at different warp to depth ratio). This feature determines the flexibility and robustness of the software, which is especially valuable when complex real fishing systems are to be modeled. We also evaluated the ability of each software to optimize the process of design and simulation in terms of time saving and efficiency. This included data reusability (i.e., ability for designing reusable user defined elements), modeling assistance (i.e., libraries/database available, templates of modeling objects, warning messages, and undo/redo commands), design capabilities (number of elements in the model, templates requirements, ease of entering input, ability of cut, copy and paste of objects, and writing comments/notes in model building activity). We further evaluated each software's simulation capability regarding visual aspects (3D-animator, real time simulation, ability for customizing the view of the model, zoom function, and multiple screen layout), efficiency (robustness, changeable in riggings and simulation setup while carrying-out a simulation, alarm setting ability, and reliability), and testability (display output variables, change in simulation speed, multiple windows during simulation run, and user pause facility).

3.4.4 Comparison between simulation results and at-sea observations

Each of the three software packages was utilized to simulate the mechanical behaviour of the Campelen 1800 trawl (i.e., geometric configuration and forces). We conducted a number of simulation tests to evaluate the effects of towing depth on the engineering trawl performance. The simulations were performed at a standardized towing speed of 3.0 knots for 7 different towing depths (250, 500, 750, 1000, 1250, 1500, and 1600m). The results were analyzed with respect to key performance measurements, including: door spread (m), wing spread (m), headline height (m), and warp tension (MT).

To evaluate the reliability/accuracy of the software, the simulation output data for trawl geometry and resistance were compared against the full-scale at sea performance of the Campelen 1800 trawl to evaluate how each software replicates real-world conditions. Full-scale observations of the Campelen 1800 trawl in action were collected during the fall of 2011 aboard the research vessel *CCGS Teleost.* Full-scale observations were collected for trawl geometry (i.e., door spread, wing end spread, and headline height) and trawl resistance (i.e., warp tension) at a standardized speed of 3.0 knots (speed over ground) and seven depths (250, 500, 750, 1000, 1250, 1500, and 1600 m) (see Gardner, 2012 and Nguyen et al., 2015). This dataset was used for the purpose of comparing full-scale observations against predictions obtained by each simulation software under the same trawling conditions (i.e., towing depths and speeds).

The results of the numerical simulations were examined to determine how well they predict (or simulate) the observed trawl performance at-sea. Several key relationships that describe the mechanical behaviour of the Campelen 1800 were examined, including: (1) towing depth and door spread, (2) towing depth and wing spread, (3) towing depth and headline height, and (4) towing depth and warp tension. Analysis of Covariance (ANCOVA) was used to statistically compare slopes of the relationships against at-sea observations, whereas paired *t*-tests were used to compare means. All of the statistical procedures were performed using the IBM SPSS Statistics software package.

3.5 Results

3.5.1 Data Requirements

DynamiT and SimuTrawl generally required fairly extensive data collection and input prior to the design and simulation process. Both software required essentially the same type of information, including data on:

- Netting panels of the trawl (e.g., material, runnage, mesh size and shape, diameter, yarn stiffness, and braiding factor);
- Strengthening ropes (e.g., material, diameter, stiffness, and mass/apparent mass);
- Floatation and footrope/footgear (e.g., material, volume, mass, and buoyancy);

- Rigging information-any combination of cables can constitute the rigging such as warp/sweeps/bridles (e.g., material, diameter, stiffness, and mass/apparent mass);
- The trawler /vessel and trawl doors.

Trawl Vision PRO required comparatively less intensive input compared to DynamiT and SimuTrawl. The software required information on:

- Netting panels of the trawl (e.g., mesh size and shape, and knots). Information on material, runnage, and stiffness are not requested;
- Strengthening ropes (e.g., length and diameter). Information on material, stiffness, and mass/weight are not requested;
- Rigging information for length and diameter of warp/sweeps/bridles. The rigging of bridles and sweeps is limited (i.e., three different standard riggings are available).

3.5.2 Design and simulation capabilities

DynamiT and SimuTrawl allow the user to create and simulate any trawl design, including complex trawling systems involving complicated riggings and multiple wingtips, without the requirement of pre-defined trawl template which is an essential requirement for Trawl Vision PRO. We found that both DynamiT and SimuTrawl can provide users the opportunity to build their own database (information about fishing gear materials) or store elements used to define a trawl in a library in order to call them back in later use. This greatly simplifies the design process as well as saves input time compared to the Trawl Vision PRO. The design and simulation capabilities of each software are described and discussed in more detail in the following sections.

- ***DynamiT***

The process of designing and simulating a trawling system in DynamiT is described in Figure 3.2. The user initiates the Trawl Gear Document and inputs all data and parameters of the trawl gear in order to build a numerical model of the fishing system. The Simulation Document is initiated separately to select simulation parameters such as towing speed and fishing depth, to run a simulation and display the calculation results in a 3D interface. The Trawl Gear Document provides different modes for the user to input the trawl gear data (e.g., Geometry mode, definition of the trawl and its rigging; Seams mode, definition of the seams between panels and connections between the trawl and the rig; Numerical mesh mode, generation of a “numerical” trawl gear; and Layout printing mode, trawl design view). The Simulation Document is used to run, control a numerical simulation, and to analyze its output results (Figure 3.2).

The Trawl Gear Document of DynamiT, which is also defined as a Trawl gear file (*.trg), is only a single window document. All objects and elements regarding the trawl system that are defined by the user are displayed in this trawl design window. An example of a design of the Campelen 1800 trawl in a single window is shown in Figure 3.3a. Entering and defining all the trawl design components (e.g., entering all the netting panels and strengthening ropes/cables/other parts of the rigging, and the seams-assembling the panels together and connecting the net to the rig; defining the netting sections of the panel, the floatation and the footgear/footrope) are generally found to be very straightforward. For convenience and accuracy, the user is able to create symmetrical netting sections and strengthening ropes, rather than slowly duplicating components. These items can be stored in a library for later use, which speeds data entry and time to simulation. Inputting a trawl design into DynamiT is relatively simple for individuals with a knowledge of trawl design and have a basic knowledge of the Windows operating system (e.g., popup menu and context menu). The Trawl Gear Document in DynamiT also allows the user to define a virtual trawl or construct a "numerical" trawl gear that will be used by the Simulation Document to run calculations. However, understanding and learning how to build an efficient "numerical mesh" and generate a proper virtual trawl could be the most difficult part for the user depending on the trawl structure characteristics, but it is an important step to help optimize calculation time and improve reliability of the simulation.

The Simulation Document in DynamiT, which is also defined as a Simulation file (*.sim), is a single window (Figure 3.3b) and divided into three sub-windows: 1) the main 3D view where the simulated trawl gear is drawn and visualized. Users can modify the view angle, zoom in/out, and access the context menu of the Simulation Document; 2) the sub-window views the intermediate results during calculation in the simulation output, the information about the selected bars and the current results; and 3) the sub-window displays the number and date of result-files. In the Simulation Document, the user can run calculations and analyze the results. The numerical simulation provides global information relative to the trawl gear such as trawl geometry (e.g., door spread, wing spread, headline height, and swept area) and forces (e.g., warp/bridle tensions and bottom contact forces produced by doors and footgear) across different towing speeds and depths (Figure 3.2). Pictures and video animations can also be produced inside this document. It also allows users to determine the bottom contact force of trawl gear components (e.g., doors and footgear) by selecting "bottom feedback" from within the Simulation Document. The 3D view will show vertical bars extending from the contact nodes, which are colour coded according to load in the same way the trawl is presented (Figure 3.3b). DynamiT also allows the user to optimize the design process by changing input parameters during the simulation. (i.e., modify simulation input and trawl design parameters/riggings from the design window to update a currently running simulation).

DynamiT, however, has its shortcomings. The system is not truly able to represent all physical phenomena in detail (i.e., input all the data detailing the trawl). In fact, mathematical models of numerical simulation that are supposed to represent the actual phenomena have to be simplified so that the user can manipulate them to be solved by computers. Certain objects and gear elements are modeled and simulated assuming some approximations because of limitations in computational capability (e.g., desktop computers) and gear modeling scientific theory and knowledge. Numerical simulations are performed using certain assumptions regarding hydrodynamics (e.g., the trawl gear does not affect the flow field and is towed in still water, though current can be simulated in two different layers with any direction; the sea surface is not simulated though gear objects, for instance surface floats, at the sea surface can be simulated), dynamics (e.g., any change of parameter is taken into account instantaneously, the sea is quiet/no swell), doors (e.g., the angles of doors are constant relative to the flow direction, lift and drag coefficients are constant), seabed (e.g., no relief on the ground, no door spreading effect due to its digging effect in the substrate), footgear (i.e., the diameter of bobbins/rubber discs are not taken into account), and catch (e.g., the catch is not simulated).

- ***SimuTrawl***

The process of designing and simulating a trawling system in SimuTrawl is described in Figure 3.4. The user initiates the process by inputting all data and parameters of the trawl gear in Design Mode. The user creates netting panels for the trawl, including large mesh panels and small mesh panels using the actual parameters of a trawl. Like DynamiT, once all of the data relevant to the trawl gear are entered, SimuTrawl also needs a numerical mesh of the trawl in order to run the simulations. This step involves converting large mesh panels in the Design Mode into the Simulation Mode with the same properties. Similarly, the small mesh panels of the Design Mode which have the polygonal shape, must also be converted to large mesh panels for simulation which have the same shape and properties based on the approximation methods. The approximation function reduces the huge amount of meshes and mass points of a real trawl by merging many meshes into a numerical mesh. Unlike DynamiT which allows the user to create a trawl design, including its rigging configurations, in only a single window mode, SimuTrawl requires the user to complete the attachment of floats and footgear, as well as forward parts of the trawling system (e.g., trawler, trawl doors, and warp/sweeps/bridles) in another mode which is known as the Simulation Mode (Figure 3.4, 3.5a). From our experience, the process of designing a trawl in SimuTrawl took longer than DynamiT. The time and effort required to make the connections between panels (assembly of the trawl net), especially for vertical connections (i.e., connecting all the upper and lower panels together manually) was not insignificant, while this is done automatically in DynamiT. Finally, once the design process completed, another step is further required to convert the design data in the form of a design file (*.trw) into the simulation data of a simulation file (*.trs) which will be used in the Simulation Program (see Figure 3.4).

The Simulation Program of SimuTrawl is used for simulating and predicting the engineering performance of a trawl (Figure 3.4). There are no major differences in the procedures of running a simulation between SimuTrawl and DynamiT. They both have the ability to change navigation and calculation parameters during the simulation. They provide users with the same type of simulation output, including trawl shape (e.g., distance between doors, wing-ends, headline and fishing line, and swept area) and trawl resistance (e.g., tension on the warp, doors, bridles, and net) (Figure 3.4). Any noticeable differences were related primarily to different simulation capabilities between the software packages. The user of DynamiT can modify the numerical mesh of the trawl in the Design Document and force the calculation module to take it into account for the simulations. By comparison, a large mesh panel created for the SimuTrawl simulation is unable to be modified once created. Another difference between the two softwares is the ability to check and/or display the simulation output instantly or not. In DynamiT, the user is required to identify in the Design Document every parameter (e.g., horizontal and vertical openings of the trawl) that needs to be measured, whereas users of SimuTrawl can simply check for any interesting simulation parameters immediately in the main 3D view where the trawl is drawn, which is very convenient (Figure 3.5b). However, SimuTrawl is unable to complete the calculations/simulations by itself. Instead the user has to complete a simulation based on looking at the vibration of the gear element suppressed state (i.e., behaviour of gear element is steady state is the time to finish the calculation). Whereas, the DynamiT is able to terminate (i.e., complete) a simulation once the calculation process is completed. Another major difference between the two software is that the DynamiT can calculate an initial shape where all the simulated trawl gear is spread on a single line. This feature can be used to optimize the calculation time which is not developed for the SimuTrawl.

- ***Trawl Vision PRO***

The process of designing and simulating a trawling system in Trawl Vision PRO is described in Figure 3.6. The Trawl Vision Designer (TVD) allows the user to navigate through a library of trawl templates that have been pre-entered into the software. If a suitable trawl design cannot be found, the user can request the developer to produce a template, which we found was easy and straightforward. Once the user selects a trawl design, it is loaded into the Trawl Editor (Figure 3.7a) in which the user can modify parameters for netting panels (e.g., twine diameter, mesh size, number of meshes, and cutting/tapering ratio) and lacing ropes/cables (diameter and length). However, only limited rigging configurations are available to the user. Unlike DynamiT and SimuTrawl, the Trawl Vision PRO software has a highly simplified user interface that can significantly reduce time and effort required by the user to design and simulate a trawl gear.

A series of helpful coefficients (e.g., horizontal/vertical coefficients and angular coefficient) or rigging adjustment options (e.g., backstrops offset, warp offset, and bridle offset) are developed for the Trawl Vision Simulator which enable the user to control the simulation performance.

However, unlike DynamiT and SimuTrawl, there does not appear to be a numerical mesh (virtual trawl) model within Trawl Vision PRO for the calculation of trawl shape and performance. The user is not really aware of how calculations are being performed or which assumptions are being made regarding the theory of trawl hydrodynamics. Trawl Vision PRO is not able to simulate the effect of side current acting on the trawl or the ability to predict downward forces of gear components on the seabed, whereas this capability is developed in both DynamiT and SimuTrawl. Given the lack of parameter input by users (see section 3.5.1 above) and the speed at which simulations are generated (< 1s), it would appear many assumptions are being made about trawl gear elements and their effect on the dynamic behaviour of trawls.

The simulation program (Trawl Vision Simulator-TVS) is where the user can visualize the 3D view of the trawling system (Figure 3.7b). The graphic interface is exceptionally well engineered, creating a very user friendly experience. Users can even view the 3D vessel and other trawl gear components (i.e., trawl doors and vessel) as part of their simulation. The software comes with a library of vessels and doors pre-loaded. More can be requested by contacting the software developer, which we found was easy and straightforward. Once the trawl, vessel, and doors are selected, the time to produce a simulation is very fast (< 1s). The speed of the simulation together with quality of the graphics make this software a very useful tool for demonstration and training purposes.

3.5.3 Comparison between simulation results and at-sea observations

Comparison of the DynamiT simulations against at-sea observations are shown in Figure 3.8 and Table 3.1. The simulations predicted that door spread increases linearly with increasing towing depth, and this showed good agreement with at-sea observations, with no statistical difference in slope ($F=3.360$; $p=0.097$) or mean ($t=1.794$; $p=0.123$) when comparing the two datasets. The mean wing spread produced using simulation was significantly lower than those observed at-sea ($t=6.337$, $p<0.001$), but not different in slope ($F=1.526$, $p=0.245$). Similarly, the mean headline height produced using simulation was significantly lower than those observed at-sea ($t=16.016$, $p<0.001$), but not different in slope ($F=0.017$, $p=0.900$). And finally, the mean warp tension produced using simulation was also significantly lower than those observed at-sea ($t=7.415$, $p<0.001$), but not different in slope ($F=1.503$, $p=0.248$).

Comparison of the SimuTrawl simulations against at-sea observations are shown in Figure 3.8 and Table 3.2. The simulations predicted that door spread increases linearly with increasing towing depth, however the values differed significantly in both their mean ($t=8.007$, $p<001$) and slope ($F=6.434$, $p=0.030$) when compared against at-sea observations. Predictions of wing spread were statistically different in their mean (t=-

6.543, $p<0.001$) and slope ($F=95.098$, $p<0.001$). Predictions of headline height showed a decreasing relationship with increasing towing depth, which was different in slope ($F=28.402$, $p<0.001$) when compared to at-sea observation, but not mean ($t=-0.860$, $p=0.423$). And finally, the mean warp tension produced using simulation was significantly higher than those observed at-sea ($t=-6.213$, $p<0.001$) as well as different in slope ($F=19.171$, $p<0.001$) compared to our at-sea observations.

Comparison of the Trawl Vision PRO simulations against at-sea observations are shown in Figure 3.8 and Table 3.3. The simulations predicted that door spread increases linearly with increasing towing depth, showing no difference in the slope of the relationship ($F=0.390$, $p=0.546$) compared to at-sea observation, however the mean value was statistically lower ($t=-69.690$, $p<0.001$). Predictions of wing spread were statistically different in their mean ($t=14.378$, $p<0.001$) and slope ($F=6.384$, $p=0.030$). The mean headline height produced using simulation was significantly lower than those observed at-sea ($t=-6.008$, $p<0.001$), but not different in slope ($F=0.282$, $p=0.607$). And finally, the mean warp tension produced using simulation was significantly lower than those observed at-sea ($t=-8.090$, $p<0.001$), but not different in slope ($F=1.948$, $p=0.193$).

3.6 Discussion

This study provides useful knowledge regarding the strengths and limitations, capabilities and reliabilities, for three commercially available trawl simulation software packages. I evaluated their ability to simulate the Campelen 1800 survey trawl at varying towing depths and then compared these predicted values to full-scale observations of the trawl. As the authors are independent of the developers, I feel this evaluation was unbiased and objective. Every effort was made to learn and apply each software equally well. Table 3.4 provides a summary of our evaluations and impressions of each software. While we recognize that we may have missed subtle features of a particular software, I do believe we have made a valuable and objective comparison of the software. The goal is to inform potential users which software is best likely to meet their needs, and is not meant to be an endorsement of any of the software by the authors.

With regard to DynamiT, we found the software to be well established among gear manufacturers and researchers, as well as scientific literature available to document its development and application. We attribute these observations to the fact that it has been commercially available for many years and was developed by a publically funded not-for-profit organization. One of the major strengths of DynamiT is that it allows users to input a large number of the actual parameters of a trawl gear and then uses this information to solve the momentum equations, taking into account the hydrodynamic forces applied on each part of the gear at the same time. However, like many other numerical modeling methods, the calculation method of DynamiT still relies on a number of modeling assumptions, reducing confidence of predicted values. The difference (-22.3%) between simulated and full-scale values of warp tension observed in this study may be such an example. There are many factors that could contribute to this difference. In DynamiT simulation, it is assumed that there is no spreading effect of the trawl doors (due to its shearing effect with the substrate) because of modeling simplification reasons.

In addition, water current (either due to towing movement or natural conditions, e.g., tide, wind, and swell currents) are supposed to be independent of the trawl (i.e., the trawl does not perturb the water velocity). Moreover, the footgear height is not simulated with a high degree of fidelity (e.g., diameter and spacing of rubber disks). In fact the drag of trawl doors, netting, and footgear components are known to contribute significantly to the drag of the whole trawling system (Folch et al., 2008). However in real fishing conditions, drag measurements will contain uncertainty due to natural variation in oceanographic conditions (e.g., current, wind, and swell) (Fiorentini et al., 2004 and Sala et al., 2009). Therefore, the difference in warp tension observed between dynamic simulation and full-scale observations in this study should be considered and interpreted with caution. In terms of reliability, we also demonstrated that the headline height of the trawl predicted by DynamiT was significantly lower than that observed at-sea. This finding is consistent with the results from Nguyen et al. (2015). Such differences have also been commonly recognized by other DynamiT users (K. Zachariassen, pers. comm. and J. Olsen, pers. comm.) as one of the limitations of this simulation software. Based on our evaluation, we recommend the software is most suitable for individuals with a good knowledge of trawl design and material for construction, while at the same time requiring accuracy and precision in simulated values.

With regard to SimuTrawl, we found the software to be well documented in terms of its development, but only a few examples of its application by users in industry or the scientific community. We attribute this lack of literature to the relatively young age of the software and fully expect that this will expand over time. The software is considerably useful for gear researchers, manufacturers, and trawl makers at the developing stage of trawl design and performance evaluation. Similar to DynamiT, the major strength of SimuTrawl is its ability to model a large number of the actual physical parameters of a trawl gear. However, this is also known as the most complex part of software development because of the large amount of parameters and elements of an actual trawling system. Hence, many modeling assumptions are made and some gear elements are not fully modeled, reducing confidence of the predicted values. Relevant assumptions are necessary and these create bias in predicted values compared to the real world performance. For example, SimuTrawl predicted a higher (25.4%) warp tension (i.e., drag force) than observed during full-scale at-sea fishing trials. This is attributed to the fact that the software assumes the same velocity throughout the entire trawling system (C. Lee, pers. comm.), whereas flume tank and field observations have shown there is significant turbulence, as well as a drop in water velocity within trawls (Winger et al., 2010). Based on our evaluation, we recommend the software is most suitable for individuals with a good knowledge of trawl design and material for construction, while at the same time requiring accuracy and precision in simulated values.

With regard to Trawl Vision PRO, we found the software is not well described in the scientific literature in terms of its development or its application by users for scientific research purposes. We attribute this lack of literature to the limited use of the software by the scientific community and fully expect that this will expand over time. Given the limited opportunity to define physical parameters of a trawl gear in this software, it stands to reason that a significant number of assumptions are being made within the software about mathematical modeling, as well as rigging and material properties (e.g., elasticity or stiffness and resistance coefficient). Hence, the simulated results produced by the software are of low scientific confidence and should be considered carefully when used for scientific purposes. That said, the software is a very effective tool for teaching the principals of trawl hydrodynamics, particularly because of its high quality graphical interface and high speed (virtually real-time) simulations. Based on our evaluation, we recommend the software is most suitable for individuals with a basic knowledge of trawl design and a need for teaching/learning the mechanics or trawl behaviour. It is especially well suited for educators and training institutes. The software also can be a useful tool for gear manufacturers and trawl makers to improve the existing gear and demonstrate trawl performance to fishermen (F. Rodriguez, pers. comm.). The capability on predicting downward forces of different trawl components (e.g., trawl doors, footgear) should also be developed for future development of Trawl Vision PRO software.

In conclusion, each of the software packages evaluated in this study have their own strengths and limitations. In general, they each use simulation methods to predict trawl geometry (e.g., door spread, wing spread, and headline height) as well as hydrodynamic forces acting on the trawling system (e.g., tension on the rig, in the strengthening rope, net drag, and downward forces on the seabed). Potential benefits attributed to the use of the software include: 1) ability to explore the feasibility of preliminary concepts, 2) ability to examine the effect of alterations in design and rigging scenarios, 3) ability to examine the effect of towing speed and rigging changes on trawl geometry, and 4) the ability predict forces acting on the trawl and gear components including the mechanical stresses on the seafloor by any part of the trawl. However, the precision and accuracy of the simulation predictions depends on many factors. Hence, whichever design and simulation software is used, thoroughness and caution must is advised in order to improve productivity of using the simulation method. The authors recommend the use of such software as complimentary tool in addition to flume tank testing and full-scale sea trials, particularly during the early stages of design for validating simple design concepts.

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3.8 Literature Cited

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Table 3.1: Trawl geometry and trawling resistance for the Campelen 1800 survey trawl developed using numerical simulations with DynamiT software (DS), compared to full-scale observations at-sea (FSO). Mean in meter (m) for door spread, wing spread, and headline height, metric tonnes for warp tension (MT), standard error of the mean (SE), percent change (% change), degrees of freedom (df), t-statistic, F-statistic, and p-values denoted in bold are statistically significant based on an alpha of 0.05.

	Towing depth	Door spread		Wing spread		Headline height		Warp tension	
		FSO	DS	FSO	DS	FSO	DS	FSO	DS
DynamiT Simulation vs. Full-scale at sea observations	250	53.9	55.9	17.9	17.6	2.9	2.3	10.5	7.2
	500	58.4	57.1	18.6	17.9	3.3	2.3	11.4	9.2
	750	61.0	58.4	19.1	17.9	3.1	2.4	11.5	10.2
	1000	61.2	58.5	19.1	18.0	3.0	2.4	14.3	11.4
	1250	62.0	59.4	19.4	18.2	2.9	2.1	15.4	13.0
	1500	61.0	59.5	18.9	18.2	3.1	2.2	18.6	14.3
	1600	61.8	59.2	19.1	18.1	3.3	2.4	17.6	15.0
Mean	978.6	59.9	58.3	18.9	18.0	3.1	2.3	14.2	11.5
SE	191.8	1.1	0.4	0.2	0.1	0.1	0.1	1.2	1.0
% change		-2.5		-4.8		-35.8		-22.3	
df		6		6		6		6	
t-statistic		1.794		6.337		16.016		7.415	
p-value		0.123		**0.001**		**0.000**		**0.000**	
F- statistic		3.360		1.526		0.017		1.503	
p-value		0.097		0.245		0.900		0.248	

Table 3.2: Trawl geometry and trawling resistance for the Campelen 1800 survey trawl developed using numerical simulations with SimuTrawl software (STS), compared to full-scale observations at-sea (FSO). Mean in meter (m) for door spread, wing spread, and headline height, metric tonnes for warp tension (MT), standard error of the mean (SE), percent change (% change), degrees of freedom (df), t-statistic, F-statistic, and p-values denoted in bold are statistically significant based on an alpha of 0.05.

	Towing depth	Door spread		Wing spread		Headline height		Warp tension	
		FSO	STS	FSO	STS	FSO	STS	FSO	STS
SimuTrawl Simulation vs. Full-scale at sea observations	250	53.9	42.2	17.9	20.1	2.9	3.8	10.5	11.8
	500	58.4	43.4	18.6	21.8	3.3	3.7	11.4	14.8
	750	61.0	45.7	19.1	22.9	3.1	3.5	11.5	17.0
	1000	61.2	47.8	19.1	23.7	3	3.3	14.3	18.9
	1250	62.0	49.1	19.4	24.4	2.9	3.1	15.4	21.5
	1500	61.0	52.2	18.9	25.9	3.1	2.9	18.6	23.7
	1600	61.8	57.3	19.1	26.5	3.3	2.5	17.6	25.4
Mean	978.6	59.9	48.2	18.9	23.6	3.1	3.3	14.2	19.0
SE	191.8	1.1	2.0	0.2	0.9	0.1	0.2	1.2	1.8
% change		-24.2		+20.1		+5.3		+25.4	
df		6		6		6		6	
t-statistic		8.007		-6.543		-0.860		-6.213	
p-value		**0.000**		**0.001**		0.423		**0.001**	
F- statistic		6.434		95.098		28.402		19.171	
p-value		**0.030**		**0.000**		**0.000**		**0.001**	

Table 3.3: Trawl geometry and trawling resistance for the Campelen 1800 survey trawl developed using numerical simulations with Trawl Vision PRO software (TVS), compared to full-scale observations at-sea (FSO). Mean in meter (m) for door spread, wing spread, and headline height, metric tonnes for warp tension (MT), standard error of the mean (SE), percent change (% change), degrees of freedom (df), t-statistic, F-statistic, and p-values denoted in bold are statistically significant based on an alpha of 0.05.

	Towing depth	Door spread		Wing spread		Headline height		Warp tension	
		FSO	TVS	FSO	TVS	FSO	TVS	FSO	TVS
Trawl Vision PRO Simulation vs. Full-scale at sea observations	250	53.9	30.6	17.9	21.5	2.9	2.7	10.5	7.2
	500	58.4	34.4	18.6	24.2	3.3	2.7	11.4	8.7
	750	61.0	35.4	19.1	24.9	3.1	2.7	11.5	9.9
	1000	61.2	35.8	19.1	25.2	3	2.7	14.3	10.9
	1250	62.0	36.1	19.4	25.5	2.9	2.7	15.4	12.0
	1500	61.0	36.5	18.9	25.7	3.1	2.7	18.6	13.4
	1600	61.8	36.6	19.1	25.8	3.3	2.7	17.6	14.3
Mean	978.6	59.9	35.1	18.9	24.7	3.1	2.7	14.2	10.9
SE	191.8	1.1	0.8	0.2	0.6	0.1	0.0	1.2	1.0
% change		-70.9		+23.6		-14.3		-29.9	
df		6		6		6		6	
t-statistic		-69.690		14.378		-6.088		-8.090	
p-value		**0.000**		**0.000**		**0.001**		**0.000**	
F-statistic		0.390		6.384		0.282		1.948	
p-value		0.546		**0.030**		0.607		0.193	

Table 3.4: A summary of the evaluations and impressions of each software.

Specifications	Characteristics	Ifremer DynamiT	SimuTrawl	TV PRO TRAWL VISION PRO
General Features	Developers	IFREMER	MPSL	ACRUXSOFT
	Initial release	1998	2004	2001
	Operating system	Windows 7, Windows XP Pentium IV GHz	Windows 7, Windows XP, Windows 2000	Windows 7 or 8, Windows Vista,
	Lock System mechanism	Provided	Provided	Provided
	Size	51.30 MB	3.92 MB	312.60 MB
	Available in	English, French, and Spanish	English and Korean	Spanish, English, Italian, French, and
	Type	Trawl design and simulation software: bottom trawls, pelagic trawls, twin trawls, etc.	Trawl design and simulation software: bottom trawls, pelagic trawls, twin trawls, etc.	Trawl design and simulation software: bottom trawls, pelagic trawls, twin trawls, etc.
	License/costs (USD)	9,000.00	10,000.00	10,000.00
	Website	*http://wwz.ifremer.fr/dynamit_eng/*	*http://www.mpsl.co.kr/home/eg/products/p_01/sub02.php*	*http://www.acruxsoft.com.uy/en/product.html*
	Potential users	Fishing companies, trawl designers and net makers, research institutes, fishing schools and training centers	Fishing companies, trawl designers and net makers, research institutes, fishing schools and training	Research institutes, fishing schools, training centers (for teaching and training), fishing companies
	Main purpose	Research oriented	Research oriented	Education/training oriented

Table 3.4 (Continued)

Specifications	Characteristics	Ifremer DynamiT	SimuTrawl	TV PRO
	Examples of application	Study trawl geometry and forces of new or existing trawl gears, how trawl gears can impact the seabed or how a trawl can be modified to	Study trawl geometry and forces of new or existing trawl gears, how a trawl can be modified to reduce the fuel consumption.	Study trawl geometry and forces of new or existing trawl gears, how a trawl can be modified to reduce the fuel consumption.
	Lock System mechanism	Provided	Provided	Provided
User-friendly software	User friendliness	Medium	Medium	High
	Experience required for software use	Medium	High	Low
	Ease of learning	Moderate	Tough	Easy
	Ease of using	Moderate	Tough	Very Easy
Ability for new users to self-training/using or user	Demo models	Available	Not Available	Not Available
	Run-time help	Available	Not Available	Not Available
	User's guide/manual	Available	Available	Available
	Quality of tutorial documentation	High	Medium	Medium
Modelling Assistance	Libararies and templates of simulations objects	Average	Average	Good
	Warning messages	Average	Average	Good
	Facility for designing resusable user denfined elements	Good	Good	Poor
	Undo/redo	Provided	Provided	Not Provided
Design capabilities	Templates	No	No	Yes
	Input requirement	Intensive Input Data	Intensive Input Data	Less Input Data
	Number of elements in the model	Large	Large	Small

Table 3.4 (Continued)

Specifications	Characteristics	Ifremer DynamiT	SimuTrawl	TV PRO TRAWL VISION PRO
	Current control	Possible	Possible	Not Possible
	Ground friction/seabed type	Possible	Not Possible	Possible (only for muddy
	Complex gear system design application	Possible	Possible	Not Possible
	Data reusability	Possible	Possible	Possible (only trawl doors/trawl
	Database available	Not Available	Available	Available
	Ease of entering input	Easy	Moderate	Very easy
	Numerical gear generation/assumptio	Applicable	Applicable	Not Applicable
	Writing comments/notes in model building	Possible	Not Possible	Not Possible
	Cut, copy, paste of objects	Possible	Possible	Not Possible
	Changeable in trawl gear scale	Not Possible	Not Possible	Possible
Simulation capabilities				
Visual Aspects	3D- animator	Good	Good	Very Good
	Facility for customizing the view	Provided	Provided	Provided
	Playback	Provided	Provided	Not Provided
	Zoom function	Provided	Provided	Provided
	Multiple screen	Not Possible	Not Possible	Possible
Efficiency	Robustness	High	Medium	Low
	Reliability	High	Medium	Low
	Level of details	High	Medium	Low
	Time scale for model designing	Medium	Large	Small
	Model status saving	Possible	Possible	Possible

Table 3.4 (Continued)

Specifications	Characteristics	Ifremer DynamiT	SimuTrawl	TV PRO TRAWL VISION PRO
	Interactive handling of parameters during experimentation	Possible	Possible	Possible
Testability	Display of variables	Possible	Possible	Possible
	Define variables	Possible	Possible	Not possible
	Audible alarms	Not Possible	Not Possible	Possible
	Multiple windows during simulation	Not Possible	Not Possible	Possible
	User Pause facility	Possible	Possible	Not Possible
	Towing speed control during simulation	Possible	Possible	Possible
	Warp length control during simulation	Not Possible	Possible	Possible
	Bridle/sweep length control during simulation	Not Possible	Not Possible	Possible
	Doorlegs control during simulation	Not Possible	Not Possible	Possible

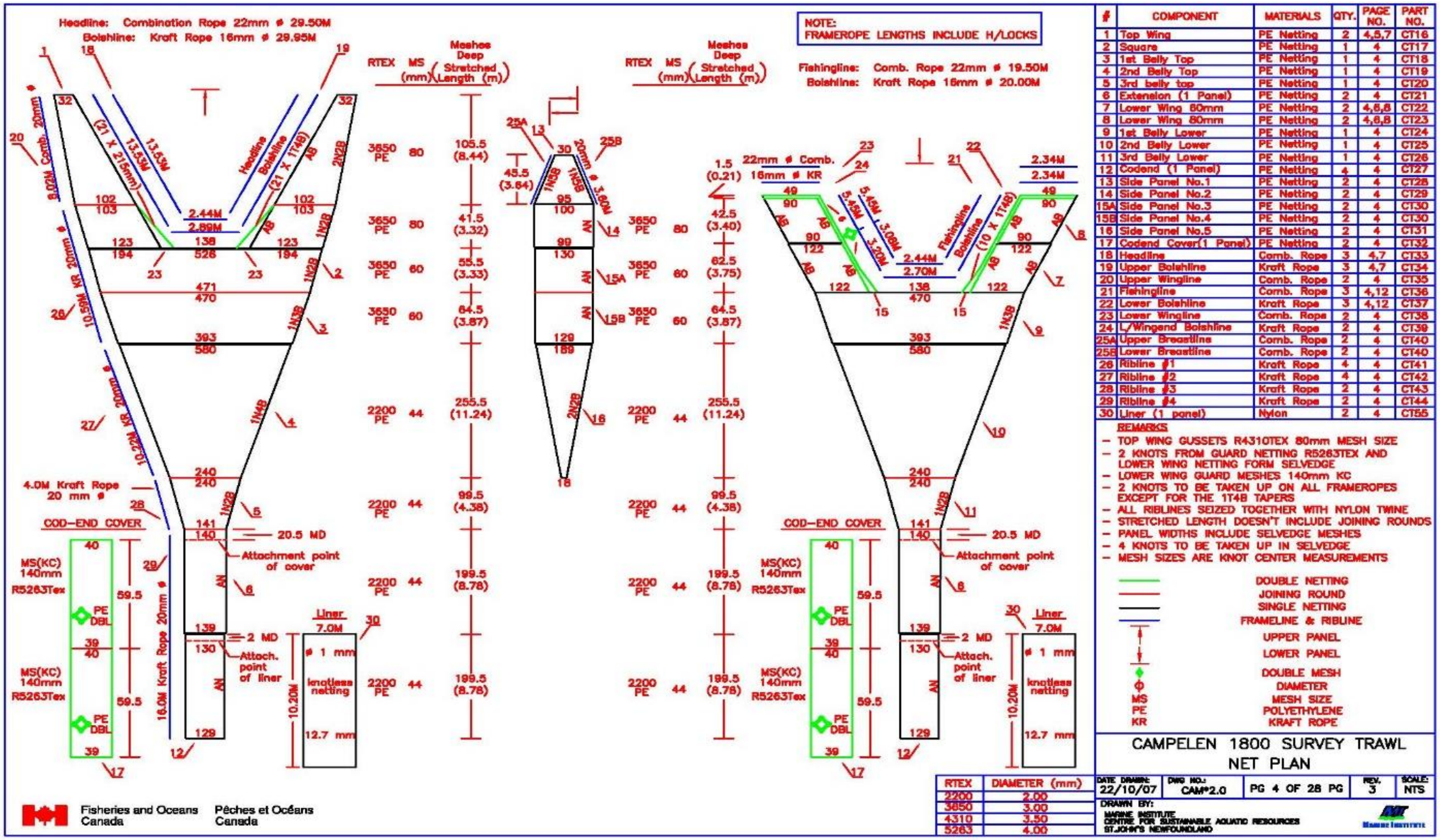

Figure 3.1: Schematic netplan of the Campelen 1800 demersal survey trawl (Walsh et al., 2009)

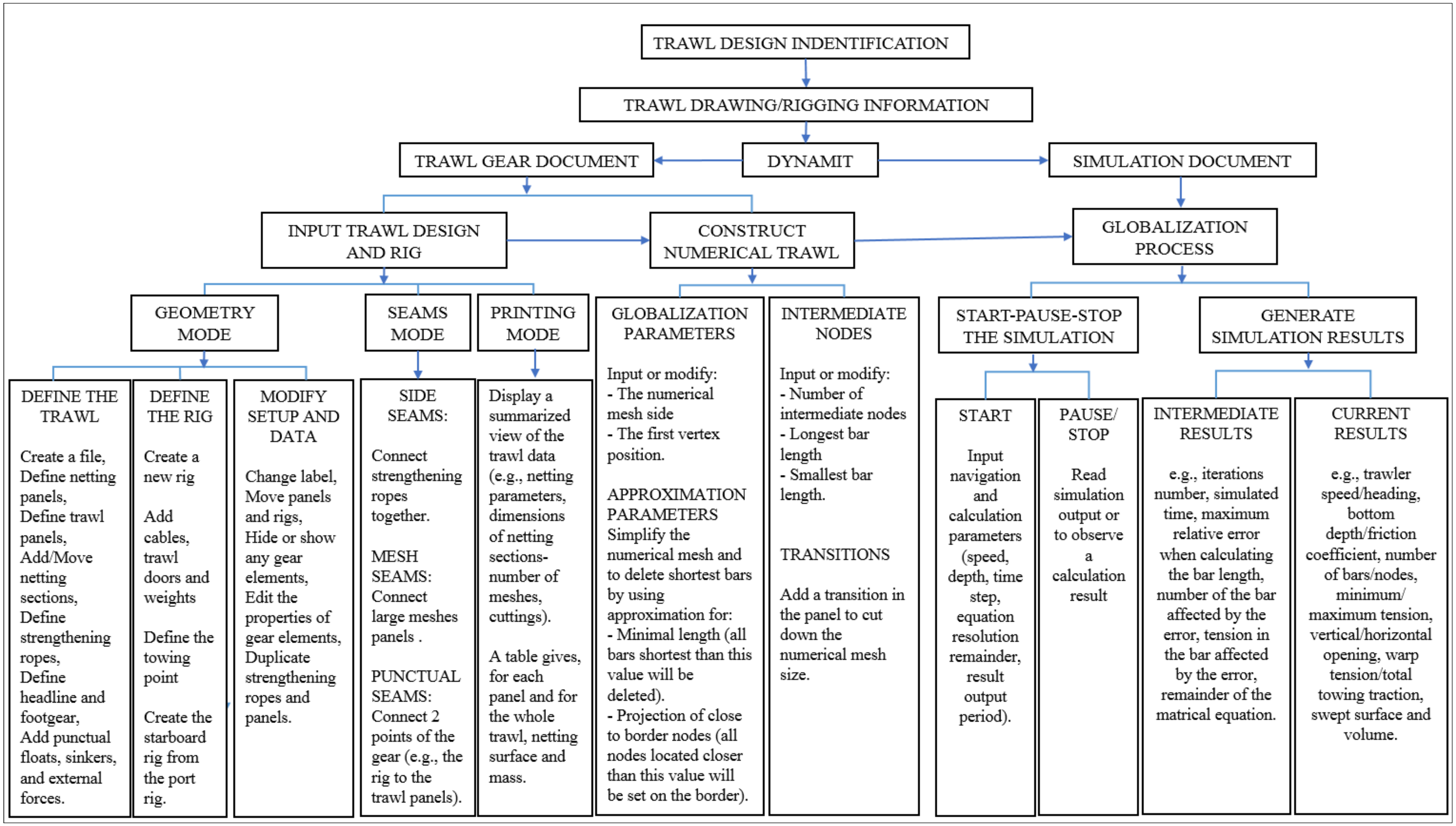

Figure 3.2: Flowchart of the DynamiT design and simulation process.

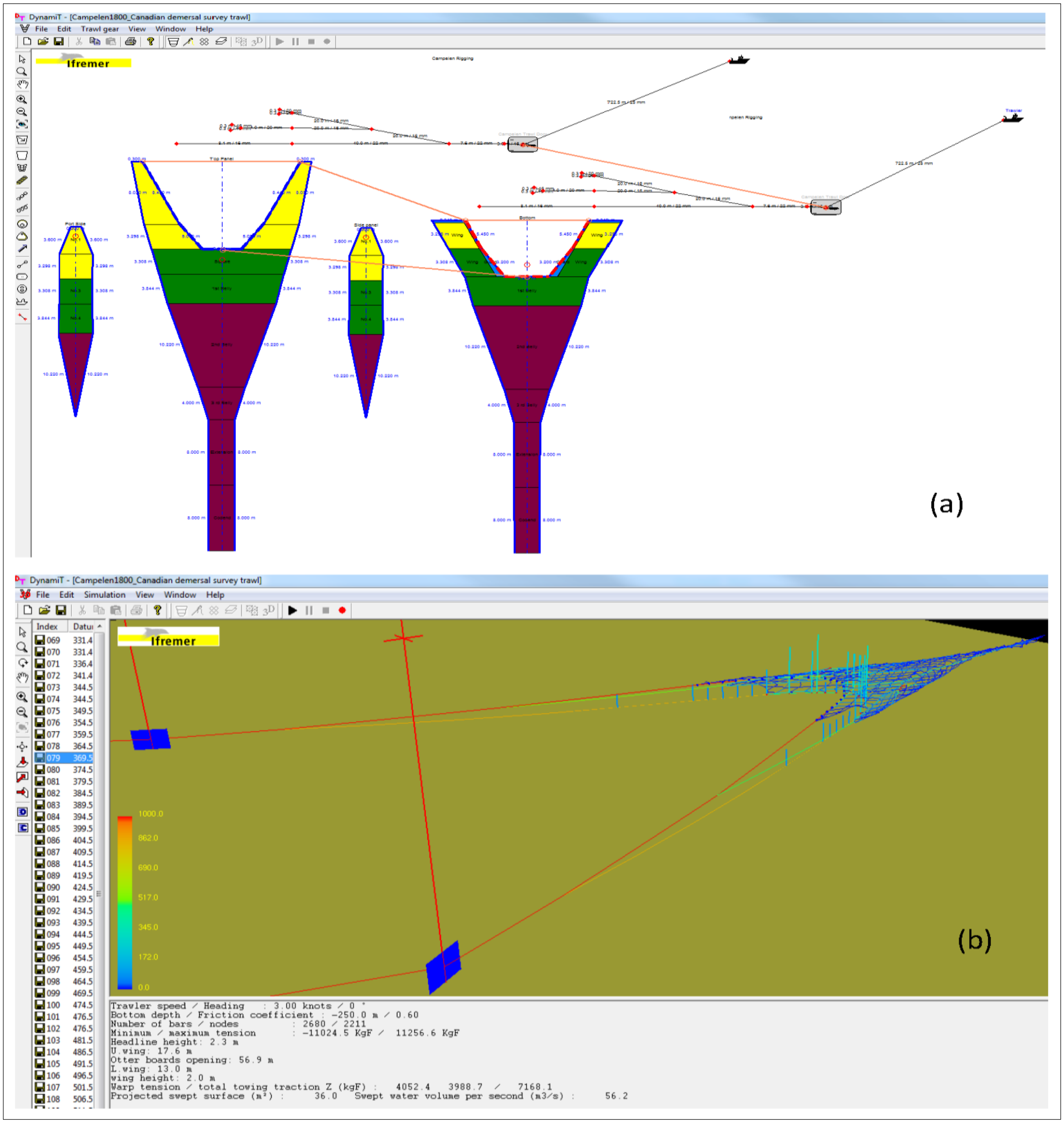

Figure 3.3: Examples of the graphic interface in the DynamiT software, including the trawl design window-Trawl Gear Document (a) and the simulation window-Simulation Document (b) of the Campelen 1800 trawl.

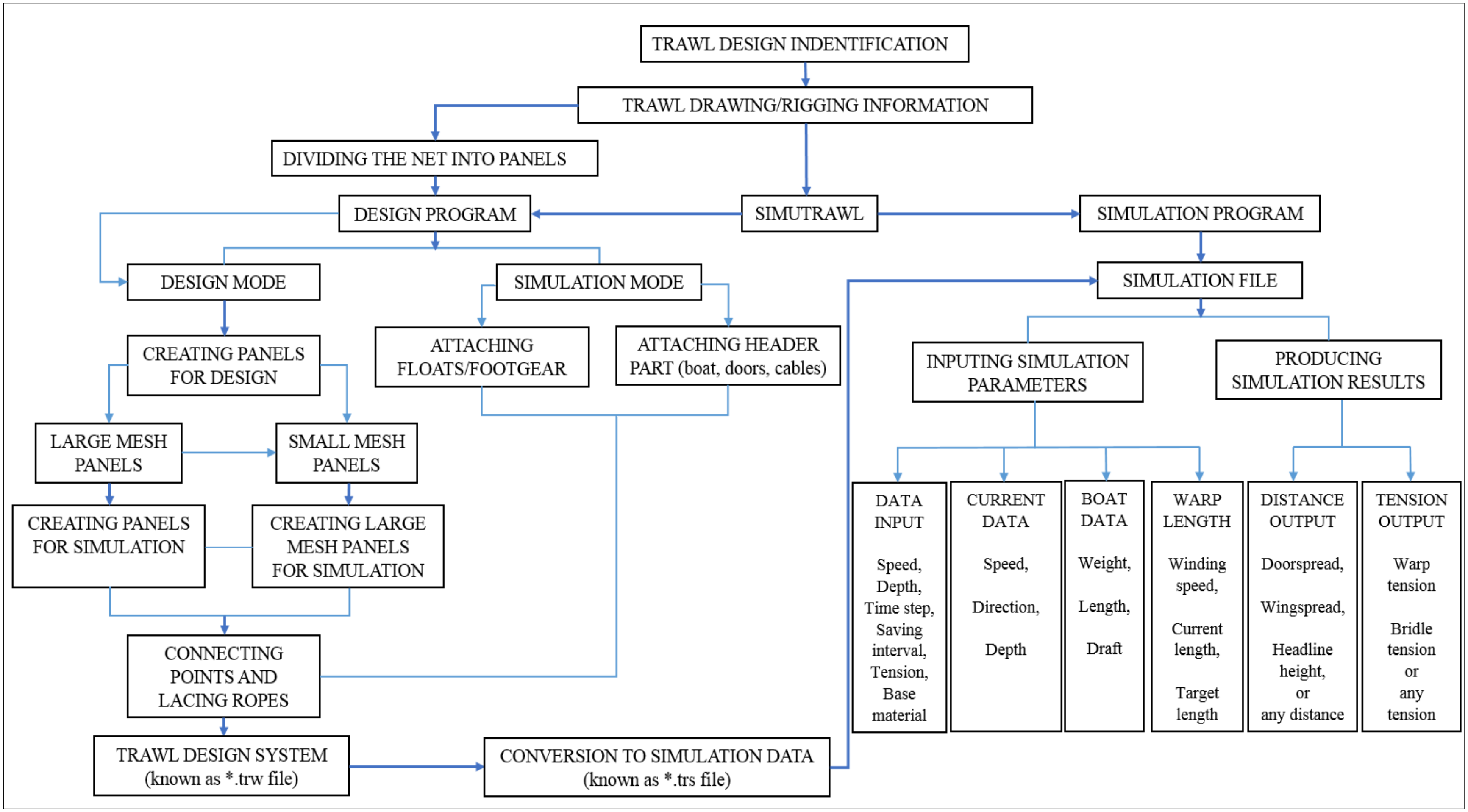

Figure 3.4: Flowchart of the SimuTrawl design and simulation process.

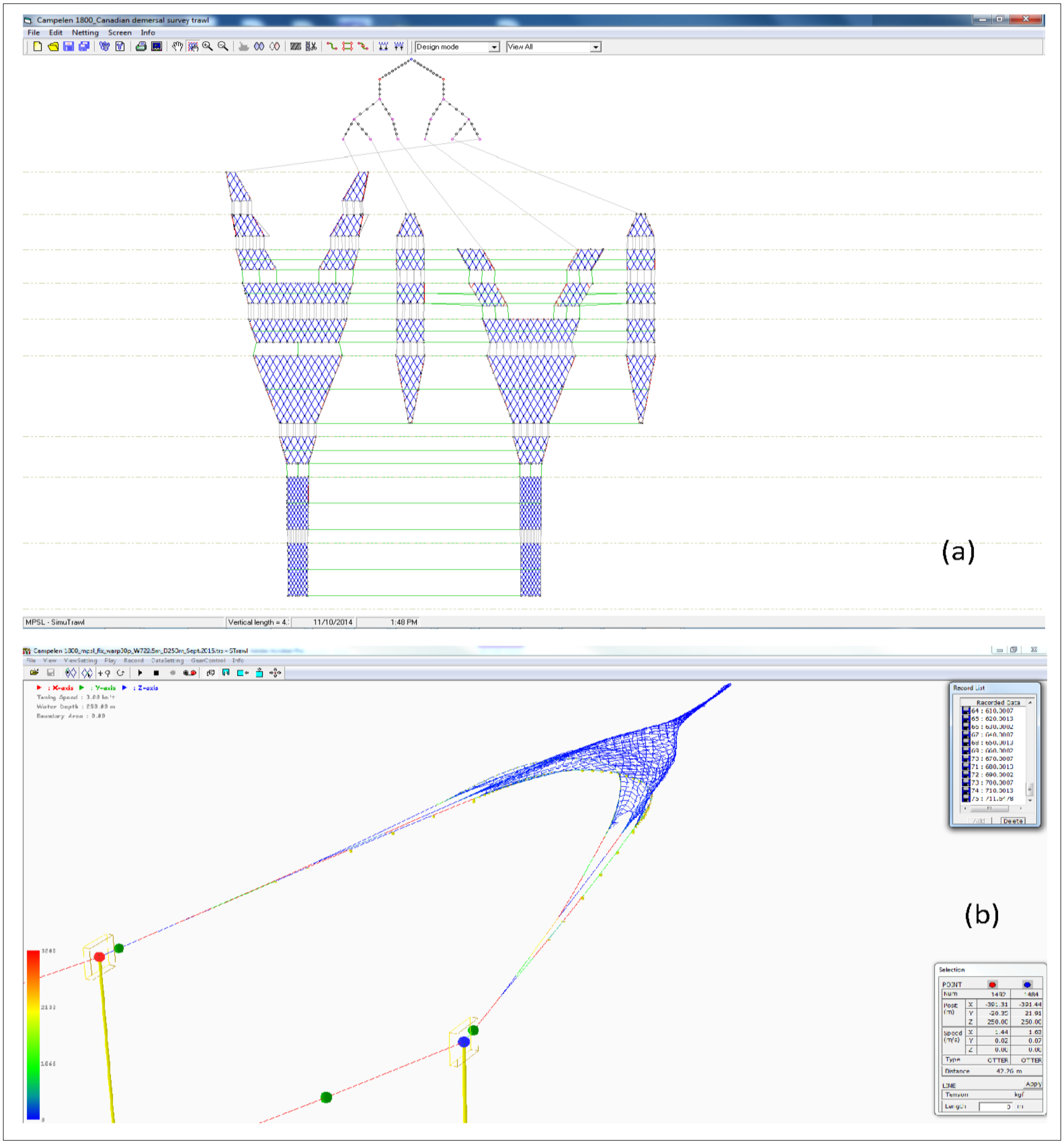

Figure 3.5: Examples of the graphic interface in the SimuTrawl software, including the trawl design mode (a) and the simulation mode (b) of the Campelen 1800 trawl.

(b)

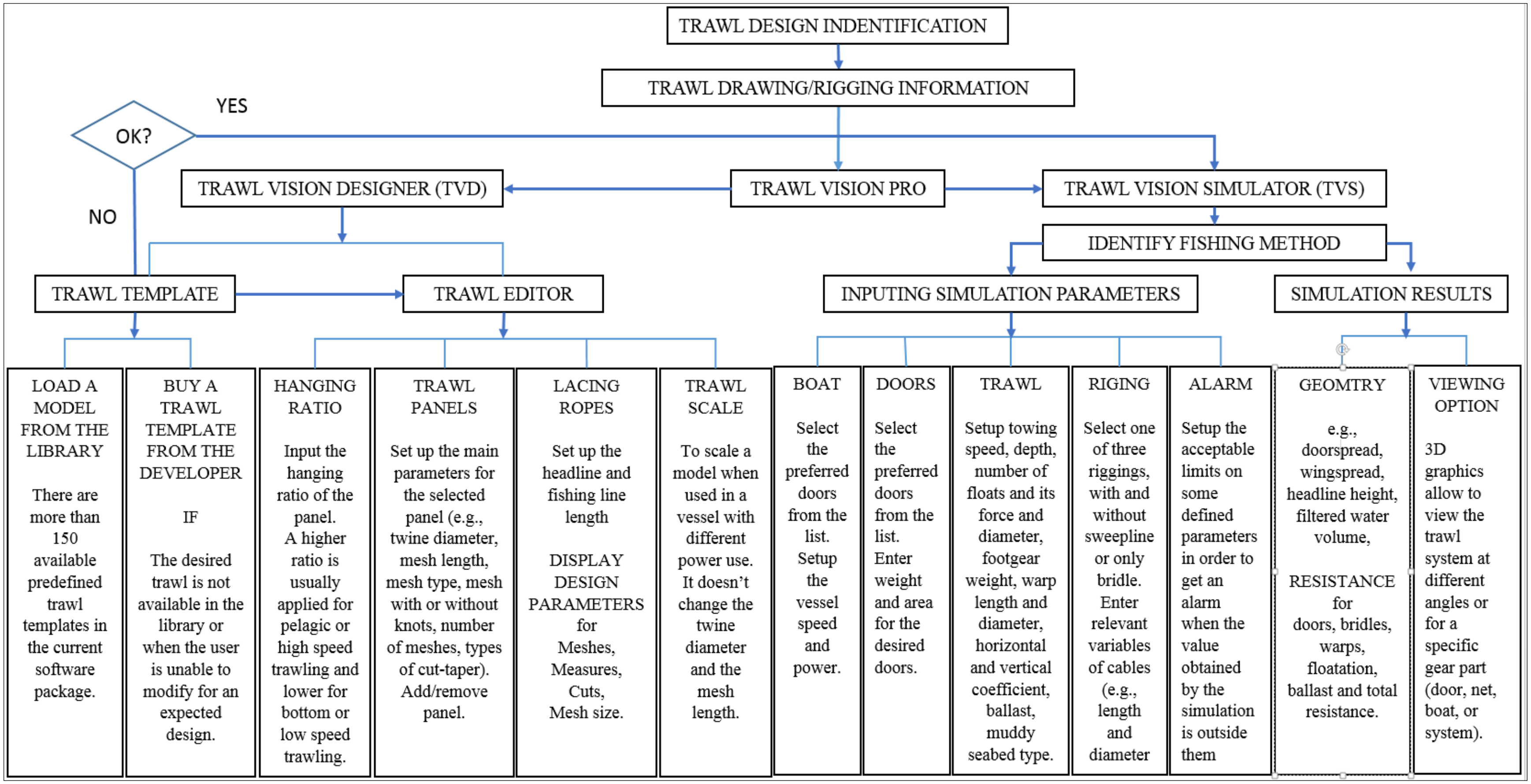

Figure 3.6: Flowchart of the Trawl Vision PRO design and simulation process.

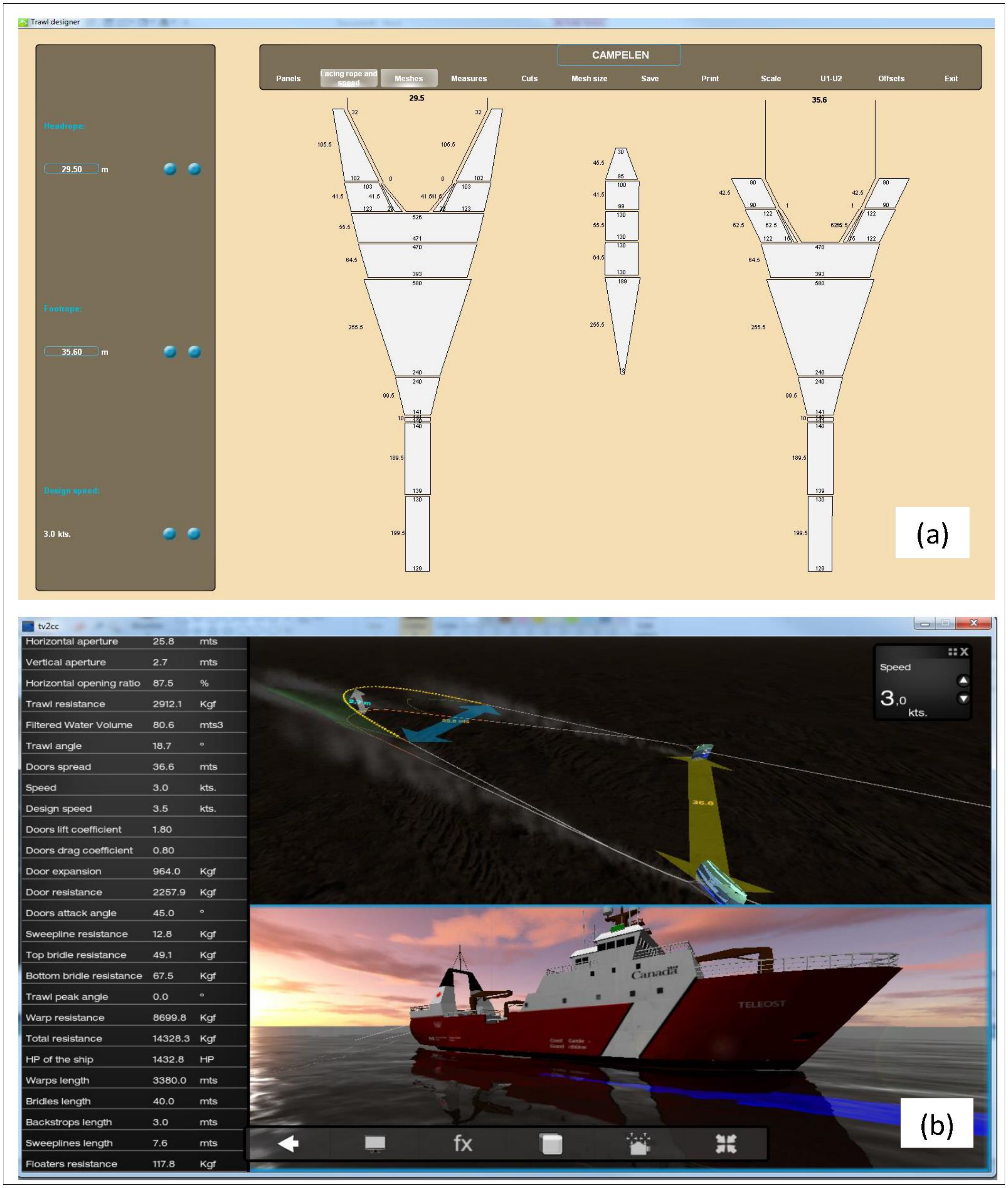

Figure 3.7: Examples of the graphic interface in the Trawl Vision PRO software, including the trawl design window (a) and the simulation window (b) for the Campelen 1800 trawl.

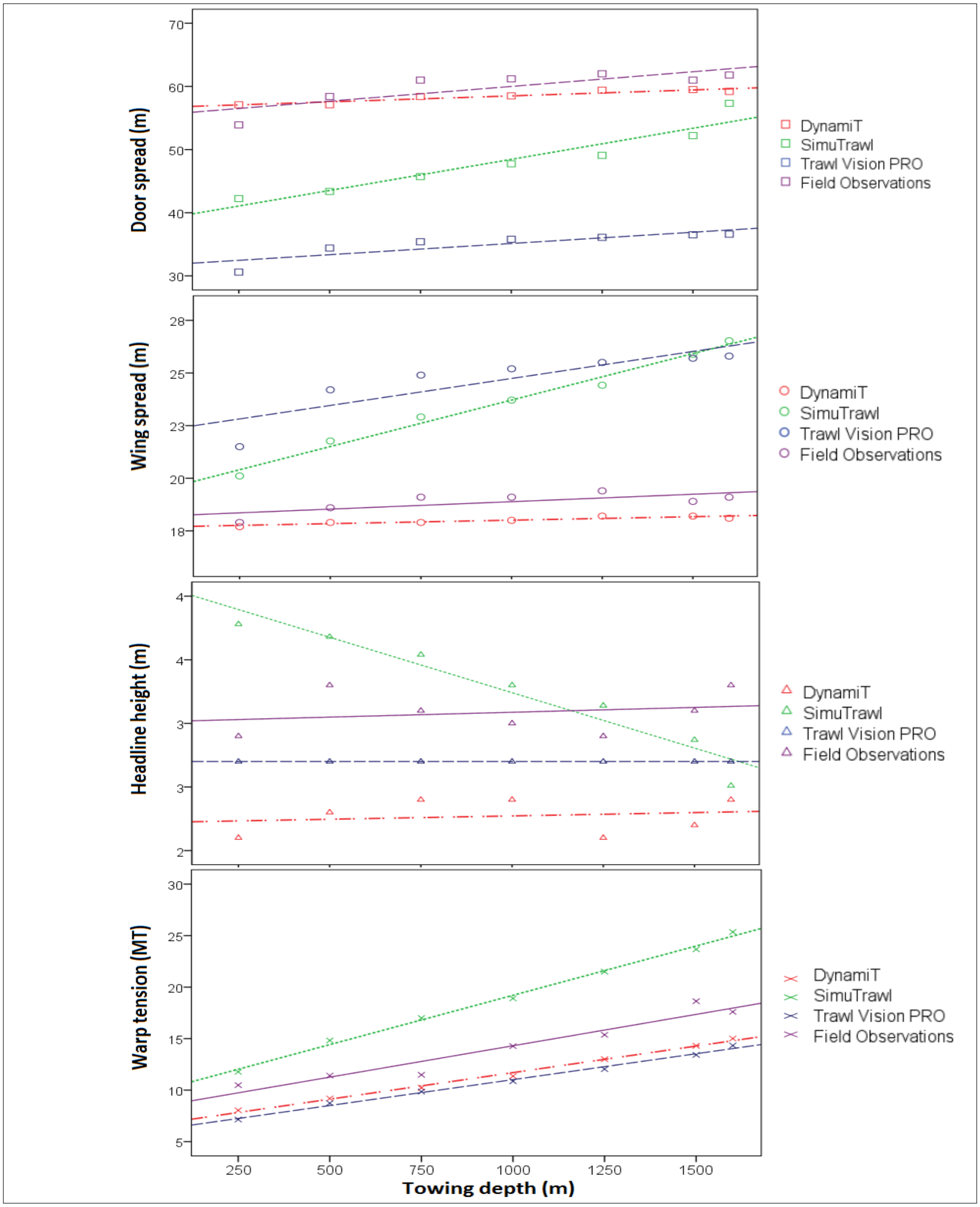

Figure 3.8: The Campelen 1800 door spread, wing spread, headline height and warp tension in relation with towing depth at towing speed of 3 knots. The best fit regression lines are shown for each scatter plot.

Chapter 4. Computer simulation and flume tank testing of scale engineering models: How well do these techniques predict full-scale at-sea performance of bottom trawls?

4.1 Abstract

A Canadian demersal survey trawl (Campelen 1800) was used to investigate the differences in trawl geometry and resistance using dynamic simulation, flume tank testing, and full-scale at-sea observations. A dynamic simulation of the trawl was evaluated using DynamiT software. A 1:10 scale model was built and tested in a flume tank at the Fisheries and Marine Institute of Memorial University of Newfoundland (Canada). Full-scale observations of the Campelen 1800 in action were collected during the 2011 fall multi-species survey aboard the research vessel *CCGS Teleost*. The numerical and physical modeling data were assessed to determine their ability to predict full-scale at sea performance of the Campelen 1800 trawl. The numerical simulation data were also compared against scale model engineering performance under identical conditions. The study demonstrates that the ideal method with which to accurately predict full-scale at-sea performance of bottom trawls or used for designing a trawling system probably does not exist. Therefore, the importance of using two or three complementary tools should be encouraged as an ideal process for designing a trawling system and/or assisting the gear development cycle.

4.2 Introduction

The method by which new fishing gears are designed and tested has dramatically changed and become more advanced and sophisticated over the last few decades. The major reasons for this continuing development in methodological process are rooted in the high cost of evaluating new gear designs at sea together with impressive improvements in the predictive abilities of computer simulation and physical models, both of which have been shown to reduce relevant expenses and potential risks for gear manufacturers and researchers (Winger et al., 2006; Prat et. al., 2008; Queirolo et al., 2009). The driving forces of increasing regulations, bycatch restrictions, and concerns over ecosystem impacts of bottom trawls have also been cited for the need for significant improvements in the way new fishing gears are designed and tested (Winger et al., 2006).

The cycle of gear development proposed today should include the use of computer simulation, physical model testing, and at-sea evaluations in a complementary manner and in a logical sequence of work, as the ideal process for designing a new fishing gear system (Winger et al., 2006). Most importantly, the use of computer-based numerical modeling and simulation is encouraged during the early stages of design for validating simple design ideas, as a fast and convenient method. The recent rise in commercially available trawl design and simulation software has significantly improved the speed and quality of design work. Today, several commercial software packages are available for purchase and use on desktop computers and tablets (e.g., DynamiT, SimuTrawl, Trawl Vision Designer and Trawl Vision Simulator, CadTrawl, and CATS). Most of these software packages have the ability to simulate the effects of different materials and design features on trawl shape and performance under different rigging and towing scenarios, as well as calculate expected mechanical stresses on the seabed (e.g., Vincent, 2000 and Queirolo et al., 2009). By comparison, testing physical models in a flume tank, which is considered the *de facto* standard for evaluating new designs and forms the backbone of the modern fishing gear development cycle (Winger et. al., 2006), is recommended in order to validate simulated values derived in previous simulation work (Queirolo et al., 2009). Benefits attributed to constructing and testing physical models include the ability to 1) explore potential defects in design; 2) examine the effect of alterations in design and rigging; 3) examine the effect of speed and rigging changes on gear geometry and orientation; 4) measure forces acting on the gear or bottom contact area of gear components such as trawl doors or footgear; and 5) measure motions of fishing gear (see discussions by Dickson, 1959; Fridman, 1986; Winger et al., 2006). Finally, evaluation of full-scale prototypes at sea is always necessary for assessing the real fishing gear performance and identifying the most successful design features and trawl components of the new fishing gear system. The accuracy of measuring and predicting trawl geometry and performance of a new gear design plays an important role in gear development process. In real fishing conditions, trawl geometry and performance can vary from tow to tow and may be affected by various factors (e.g., towing speeds, water currents, and bottom type) and increasing error in accuracy of measurements. The use of acoustic trawl monitoring sensors (e.g., SCANMAR acoustic trawl monitoring instruments) have permitted researchers to improve their monitoring of trawl performance at sea, detect any gear malfunctions and reduce variability in trawl geometry and performance (see, for example, Walsh and McCallum, 1995, 1997).

Given the high cost of evaluating new gear designs at sea, many trawl designers/researchers and manufacturers proceed with computer simulation followed by the testing of physical scale models in flume tanks. However, some might be tempted to speculate whether computer simulation might someday replace physical models or others could raise a question about how well do computer simulation and physical modeling predict full-scale gear performance at sea? Interestingly, few studies have been conducted to evaluate the accuracy/precision of numerical and physical modeling techniques in the comparison with full-scale trawl performance during the last decade. In some cases, data from physical models have been compared to full-scale trawls (e.g. Morse et al., 1992; Fiorentini et al., 1991, 1992, 2004; Sala et al., 2009), and in other cases data from computer simulations have been compared to physical models (e.g., Queirolo et al., 2009), but no clear studies exist in which all three techniques are compared, or any comparison between software, or between flume tanks. Hence, this study represents a unique and novel piece of research.

The objective of this study was to assess the accuracy of computer simulation and physical modeling approaches in predicting the full-scale at-sea performance (geometry and resistance) of the Campelen 1800 trawl. In addition, this study also investigated the ability of computer simulation to predict performance of physical models. The results are discussed in relation to the commonly used methodological approach for fishing gear design described by Winger et al. (2006).

4.3 Materials and Methods

4.3.1 Trawl design and scale engineering model specifications

The Campelen 1800 was selected as the trawl design for this study. This is the standard demersal survey trawl widely used by Fisheries and Oceans Canada on the east coast of Canada since 1995, replacing earlier versions of the Engel 145 otter trawl and the Yankee 41 shrimp trawl (Walsh and McCallum, 1997). This trawl design is known as a four panel design with cut-away lower wings and is rigged with three bridles and 4.3 m^2, 1400 kg Morgère Polyvalent trawl doors. The Campelen 1800 trawl is rigged with a 35.6 m rockhopper footgear and uses 356 mm diameter rubber disks. Trawl construction is of 4.0, 3.0 and 2.0 mm diameter polyethylene twine varying in mesh size from 80 mm in the wings to 60 mm in the square and the first bellies and 44 mm in the remaining bellies, extension and codend (see Figure 4.1 for details). The design has changed very little over time as a result of stringent standardization of construction and operational protocols (Walsh et al., 2009).

A linear scale of 1:10 was selected as the best balance between the limitations of the test facility (i.e., flume tank size), objectives of the test program, and the ability to extrapolate model results to full-scale performance. The majority of the components were custom ordered and/or fabricated in-house and the model was assembled by hand using standard trawl construction practices (see Winger et al., 2006).

4.3.2 Dynamic simulation tests

Trawl simulation software (i.e., DynamiT) developed by the French Research Institute for the Exploitation of the Sea (IFREMER) was utilized to simulate the mechanical behaviour of the Campelen 1800 trawl. The software has the ability to calculate and simulate the dynamic behaviour of virtually any trawl type, commonly referred to as dynamic simulation (Vincent 2000 and Queirolo et al. 2009). For this study, the simulations were performed for different door spreads, depths, and towing speeds. Output parameters included door spread, wing-end spread, headline height, and towing resistance (i.e., warp/bridle tension).

In order to facilitate comparison to the physical modeling, the dynamic simulations were conducted at the same door spreads as the flume tank tests in order to eliminate bias in trawl performance when comparing the two datasets. The simulations were constrained for the desired door spreads by deploying the appropriate warp and simply attaching a rope of diameter 0.0 mm between the trawl doors as a restrictor rope (referred to as restrictor rope based simulation). Specifically, we conducted a series of dynamic simulations for six different door spreads of 45.0, 50.0, 55.0, 60.0, 65.0, and 70.0 m at four different towing speeds of 2.0, 2.5, 3.0, and 3.5 knots. The trawl geometry parameters (i.e., wing-end spread and headline height) and resistance (i.e., bridle tension) of each combination of treatments were obtained.

To facilitate comparison with the full-scale observations of the Campelen 1800 trawl, the dynamic simulations were performed at a standardized towing speed of 3.0 knots and varying towing depths or we simply replicated all the tows as conducted aboard the *CCGS Teleost* during the 2011 fall multi-species survey (referred to as depth based simulation). The trawl geometry parameters (i.e., door spread, wing-end spread, and headline height) and resistance (i.e., warp tension) of each combination of treatments were documented.

4.3.3 Flume tank tests

A 1:10 scale model was constructed by the Fisheries and Marine Institute of Memorial University of Newfoundland using mainly Froude scaling principals (Tauti, 1934; Dickson, 1959; Fridman, 1973; Hu et al., 2001). The scaled model was constructed in a manner that approximates the geometric, kinematic, dynamic, and force laws of full-scale trawls. The modelling laws may be summarized as:

$$\lambda = \frac{L_f}{L_m} \qquad (1)$$

$$A_m = \frac{A_f}{\lambda^2} \qquad (2)$$

$$F_m = \frac{F_f}{\lambda^3}\frac{\rho_m}{\rho_f} \qquad (3)$$

where *L*, *A*, *F* and ρ are length, area, force and water density, the subscripts *m* and *f* refer to model and full-scale, respectively. To compensate for differences with respect to the full-scale trawl due to available twine diameter, an area scale and force scale are also used. The velocity scale is given by:

$$\lambda^{1/2} = \frac{v_f}{v_m} \qquad (4)$$

where *v* is the towing speed.

Similar scaling theory has been applied by previous researchers for designing and testing the physical performance of trawl models in flume tanks (for details, see Morse et al., 1992; Fiorentini et al., 2004, Sala et al., 2009; Queirolo et al., 2009).

To examine the performance of the scale physical model, the 1:10 model was deployed and tested at the Fisheries and Marine Institute's flume tank, located at the Centre for Sustainable Aquatic Resources (Memorial University of Newfoundland), where different towing speeds and rigging scenarios (i.e., door spreads) were assessed.

The experiments were conducted by connecting the trawl's bridles directly to the flume tank masts. In this case, the measurements were carried out at six different mast spreads (corresponding to full-scale door spreads of 45.0, 50.0, 55.0, 60.0, 65.0, and 70.0 m) and at four different towing speeds through water (corresponding to the full-scale range of 2.0, 2.5, 3.0, and 3.5 knots). For statistical comparison purposes, the physical modeling tests were repeated five times for each experimental scenario (120 runs). Estimates of the hydrodynamic performance of the model (e.g., wing-end spread, headline height, bridle tension-load ahead of the bridles) for each experimental combination of treatments (n = 120) were measured and recorded using the existing optical and data acquisition systems within the flume tank.

4.3.4 Evaluation of the full-scale prototype

Full-scale observations of the Campelen 1800 trawl in action were collected during the fall of 2011 aboard the research vessel *CCGS Teleost.* Trip 1 was conducted during September 01-08, 2011 to collect data related to towing resistance, in which observations of trawl geometry and shaft torque were collected at two speeds (3.0 and 3.5 knots speed over ground) and seven depths (250, 500, 750, 1000, 1250, 1500, and 1600 m). Using a series of well-developed relationships, these data were used to develop estimates of total thrust for the different depths (see Gardner, 2012 for more details). This dataset was used for the purpose of comparing full-scale observations against estimates of trawl resistance (i.e., warp tension) obtained by the dynamic simulation under the same trawling conditions (i.e., towing depths and speeds).

Trip 2 was conducted during November 29-December 09, 2011 as part of the fall multi-species survey aboard the same vessel. This included 48 tows at a standardized speed of 3.0 knots (speed over ground) and varying depths as determined by the survey design.

The data related to trawl depth, headline height/trawl opening, door spread, and wing-end spread were obtained using SCANMAR hydroacoustic trawl monitoring sensors attached to the fishing gear (e.g., door spread sensors are placed on each trawl door, wing spread sensors are positioned on each of the upper wing tips, depth and opening/height sensors are attached on the centre of headline). Such data were automatically logged at 5 second intervals using the NAFC (Northwest Atlantic Fisheries Centre) SeaTrawl data acquisition software. At each fishing station, the scope ratio (trawl warp length divided by fishing depth) was prescribed according to the Scope Ratio Table (Walsh and McCallum, 1997) which helps to achieve and maintain stable bottom contact of the trawl doors during towing.

4.3.5 Data analysis

The data regarding trawl geometry and resistance of the Campelen 1800 trawl obtained from the dynamic simulation, physical modeling, and evaluation of the full-scale trawl were analyzed to investigate differences in trawl geometry and resistance separately based on each technique. In our first analysis, the dynamic simulations and physical modeling datasets were compared against the full-scale at sea performance of the Campelen 1800 trawl. In our second analysis, the dynamic simulation data were compared against the predictions of the 1:10 scale flume tank model when tested under the same conditions.

The hypotheses that dynamic simulation and physical modeling accurately predict full-scale performance and secondly that dynamic simulation accurately predict physical modeling were statistically tested, requiring either parametric or non-parametric statistical test depending on the degree of homogeneity of variance within the datasets. To this end, the Analysis of Covariance (ANCOVA) and Kruskal-Wallis One Way Analysis of Variance were found to be appropriate statistical approaches to investigate these hypotheses. In addition, linear regressions and ANOVA's were also applied to describe relationships in engineering trawl performance and compare slopes among different methods (dynamic simulation vs. physical modeling vs. at-sea observations). All of the statistical procedures were performed using the IBM SPSS Statistics software package.

Different relationships that describe the mechanical behaviour of the Campelen 1800 trawl were examined including 1) door spread and towing depth, 2) wing-end spread and towing depth, 3) headline height and towing depth, 4) door spread and wing spread, 5) door spread and headline height, 6) towing depth and warp tension, 7) door spread and bridle tension, and 8) towing speed and bridle tension.

4.4 Results

4.4.1 Comparison between dynamic simulation and at-sea observations

At sea observations of full-scale trawl performance revealed no obvious trend in either door spread or wing spread in relation to towing depth (Fig 4.2 a, b). By comparison, dynamic simulation predicted increasing door spread and wing-end spread with increasing towing depth. The regression analysis indicates that the towing depth explained 66 and 67% of the variation in door spread and wing-end spread for the dynamic simulation, respectively.

Wing-end spread showed a predictable relationship with door spread for both depth based dynamic simulation and full-scale observations (Figure 4.3). The slopes of the relationships in the two methods were not significantly different ($p>0.05$). The regression model explained the variation in wing-end spread due to changes in door spread, with 98.9 and 99.8% from dynamic simulations and full-scale observations, respectively. The predictions of door spread and wing-end spread provided by the dynamic simulations were within 5% of the values observed by the full-scale at-sea performance (see Table 1 for details), but these differences were statistically significant ($p<0.05$, Kruskal Wallis test).

Headline height of the trawl showed little relationship with towing depth (Figure 4.2c). Both the dynamic simulation and full-scale observations showed little trend (positive or negative) over the depth ranges that were evaluated. Headline height of the trawl was predicted to decrease with increasing door spread according to the depth based dynamic simulation (Figure 4.4). By comparison, our full-scale observations at-sea revealed little relationship between headline height and door spread. The variation in headline height was not properly explained by door spread and towing depth in both cases. The predictions of headline height provided by dynamic simulations were significantly lower than full-scale at-sea observations ($p<0.001$, ANCOVA test), averaging 1.6 m or approximately 46% less than full-scale at-sea observations (see Table 4.1).

Warp tension showed an increase with towing depth in both dynamic simulation and full-scale observations, but with different slopes in each case (Figure 4.5). Regression model results indicate that the towing depth explained approximately 99% of the variation in warp tension in both cases. The warp tension obtained from the dynamic simulation (i.e., 9.9 MT) was significantly lower (31%) than those obtained through the full-scale observations (i.e., 14.3 MT) ($p<0.05$, Kruskal Wallis test).

4.4.2 Comparison between physical modeling and at-sea observations

Wing-end spread increased linearly with increasing door spread in both physical modeling and full-scale at-sea observations (Figure 4.3). Comparison of the data sets revealed the slopes were not statistically different ($p>0.05$). In both cases, the linear regression analysis explained approximately 98% of the variation in wing spread by changes in door spread. The differences in door spread and wing spread were not statistically significant in the two methods ($p>0.05$, Kruskal Wallis test).

There was a strong predictive relationship between door spread and headline height in the physical modeling, while there was no clear trend of this relationship for the full-scale observations (Figure 4.4). The regression analysis explained adequately the variation in headline height due to changes in door spread for physical modeling ($R^2 = 0.907$), but not the case for the full-scale observations. The headline height predicted by physical modeling was significantly higher (i.e., 14.6%) than that observed during full-scale observations ($p<0.001$, ANCOVA test).

4.4.3 Comparison between dynamic simulation and physical modeling

Wing-end spread increased linearly with increasing door spread in both the restrictor rope based dynamic simulation and physical modeling, with similar slopes in each case (Figure 4.3). However, the mean wing-end spread prediction based on the flume tank modeling was significantly higher (i.e., 6.8%) than the mean obtained from dynamic simulation at a standard speed of 3.0 knots ($p<0.001$, ANCOVA test). The regression analysis indicates that the door spread and towing speed explained 99% of the variations in wing spread in physical modeling. In dynamic simulation, the door spread explained 99.9% of the variations in wing spread while towing speed did not contribute significantly to the regression model.

Headline height decreased linearly with increasing door spread using both physical modeling and restrictor rope based simulation with the similar slopes in the two methods (Figure 4.4). However, the mean headline height predicted using dynamic simulation was substantially lower (i.e., 51.2%) than that which was predicted by physical modeling at 3.0 knots ($p<0.001$, ANCOVA test). The variation in headline height using the physical modeling was adequately explained by door spread and towing speed ($R^2 = 0.943$) while the headline height was not properly explained by these variables in the dynamic simulation.

Bridle tension showed an increase with door spread using both the restrictor rope based dynamic simulation and physical modeling, albeit with different slopes (Figure 4.6 a). The fitted relationships intersected at a door spread of 62 m, with predictions of bridle tension diverging at the lower and higher door spreads. Both techniques adequately predicted increasing bridle tension with increasing towing speed (Fig 4.6 b), with no statistical difference detected between the methods ($p>0.05$, Kruskal Wallis test). Combined together, our regression analysis indicates that more than 98% of the variation in bridle tension can be explained by door spread and towing speed in the dynamic simulation and physical modeling ($R^2 = 0.980$ and 0.992, respectively).

4.5 Discussion

This study showed that the use of dynamic simulation and physical modeling provides valuable knowledge regarding the strengths and limitations of each approach and how they could be used to predict the full-scale at-sea engineering performance of bottom trawls. Specifically, we found there was a good agreement between the dynamic simulation and full-scale observations in predicting the main performance parameters of the Campelen 1800 trawl, such as door spread and wing-end spread, but not for headline height and resistance (i.e., warp tension). When comparing physical modeling and full-scale observations, there were generally consistent predictions in terms of door spread, wing-end spread and headline height. Both the dynamic simulation and physical modeling had similar predictions in wing-end spread and resistance (i.e., bridle tension), but not for headline height.

With regard to headline height, our results demonstrated that predictions provided by dynamic simulation (3.0 knots) were significantly lower than those predicted by physical modeling or observed at-sea. Such differences have been commonly recognized by the DynamiT users (K. Zachariassen, pers. comm. and J. Olsen, pers. comm.) as one of the limitations of this simulation software. In contrast, Queirolo et al. (2009) who conducted a comparison between dynamic simulation and model testing of a Chilean trawl design found that the headline height predictions based on the dynamic simulation are higher than values obtained by the flume tank modeling. We speculate that this difference may be related to a difference in the set-up of the simulation and/or a difference in trawl design (Fiorentini et al., 2004). In the current study, the simulations were carried out in which the door spread was artificially constrained at desired distances similar to the way the flume tank operates. This was expected to eliminate biases in trawl geometry performance when comparing the simulation data against model data. The use of a restrictor rope to physically control door spread has been previously investigated for bottom survey trawls (e.g., Campelen 1800 trawl) as a method to reduce variability in door spread with towing depth in order to minimize wing spread variations (up to 25%) and hence reduce variability in resulting estimates of stock abundance (see Engås and Ona, 1991, 1993; Walsh and McCallum, 1996; Fréchet, 2000). In our study, it should be noted that the DynamiT software is normally intended to fully and freely simulate the whole trawling system (B. Vincent, pers. comm.). This is one of the strengths of the numerical approach in that it allows the effects of fishing depth, warps and doors to be simulated (M. Borstad, pers. comm.). Given such advantages of the simulation method compared to physical modeling (i.e., flume tanks do not normally simulate the full trawling system in its working environment), the headline height predicted by the DynamiT without constrained door spread was still seen to be significantly lower (i.e., approximately 45%) than it was predicted by the full-scale-at sea performance. By comparison, differences in headline height between physical modeling and at-sea observations were smaller (14%). We speculate that this difference may be attributed to scale effects, manifested as differences in trawl performance (Christensen, 1973; Hu et al., 2001; Fiorentini et al., 2004). Finally, our observation that the flume tank overestimated headline height compared to full-scale performance is not supported by Morse et al. (1992). The authors found that physical models underestimated headline height observed from full-scale prototypes. This difference may be attributed to a difference in trawl models (Fiorentini et al., 2004).

The tendency of door spread and wing-end spread to increase with towing depth has been recognized in other studies (see Walsh and McCallum, 1996, 1997; Fréchet, 1996; McCallum and Walsh, 1999; Bertrand et al., 2002). The results from our dynamic simulation of the Campelen 1800 trawl support this phenomenon, however no such trends were observed for our full-scale observations. While the depth range was more than sufficient, we suspect our sample size may have been too small to statistically detect a relationship. This type of data has been shown to be inherently variable (e.g. Walsh and McCallum, 1997 and Bertrand et al., 2002) and increasing the sample size may have improved model fit.

With regard to predicting the drag of a trawl, both dynamic simulation and physical modeling demonstrated good agreement in predicting the bridle tension (or net drag). This finding is not consistent with the results from Queirolo et al. (2009) who documented a considerable difference (i.e., 13-23%) using the two methods. The different results between these two studies may be explained by the differences in how a simulation was set up and conducted. In the case of warp tension (or total drag) in our study, a significant difference was observed between the simulation testing and full-scale observations. There are different factors that could be attributed to this difference. In real fishing conditions, drag measurements will contain uncertainty due to natural variation in oceanographic conditions (e.g., current, wind, and swell) (Fiorentini et al. 2004 and Sala et. al., 2009). By comparison, the resistance (i.e., warp tension) predicted by dynamic simulation must be considered carefully with caution. For example, there is no spreading effect of the trawl doors due to its shearing effect with the substrate because of no relief of the seabed. In addition, the trawl gear does not affect the fluid flow and is towed in still water. Moreover, the footgear height is not simulated with a high degree of fidelity (e.g., diameter and spacing of rubber disks). In fact, the drag regarding trawl door and footgear components and/or their operational contact with the seabed (e.g., penetrating into the seabed) normally forms a significant drag component of the whole trawling system. These limitations of the dynamic simulation method could potentially explain why the drag measurements obtained in the dynamic simulation tended to be lower (or different) than of the full-scale observations at sea.

In conclusion, all of the methods used in this study have their own weakness and merits. The ideal method with which to accurately predict full-scale at-sea performance of bottom trawls or for designing a trawling system probably does not exist. The precision and accuracy of the predictions depends on many factors. Whichever method is employed, thoroughness and care must be emphasized in order to reduce bias in predicted values. The choice of method will be largely determined by the specific purposes of a design/experiment and the financial and material resources available. For example, a simulation tool should be used for assessing the relative effect of a gear modification to a trawling system (e.g., modify a length, floatation, twine diameter, and mesh size, etc.) at an affordable cost. Whereas, physical modeling in a flume tank is best designed for investigating the effects of rigging and modification changes on gear behaviour and performance visually and in a direct way. Therefore, the importance of using two or three complementary tools should be considered as the ideal process for designing a trawling system and/or assisting the gear development cycle.

4.6 Acknowledgments

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Table 4.1: Summary statistics of trawl geometry and resistance parameters for the Campelen 1800 shrimp trawl under towing speed of 3.0 knots.

Evaluation method	Variable	N	Mean	STDEV	Min.	Max.
Restrictor rope based simulation *(i.e., door spreads were constrained at desired distances*)	Door spread (m)	6	57.5	9.4	45.0	70.0
	Wing spread (m)	6	17.0	1.9	15.1	20.3
	Headline height (m)	6	2.0	0.5	1.4	2.8
	Bridle tension (MT.)	30	5.6	0.6	5.0	6.6
Depth based simulation (*i.e., replicated the survey tows*)	Towing depth (m)	48	559.7	396.9	139.0	1422.0
	Door spread (m)	48	57.0	1.4	53.9	59.1
	Wing spread (m)	48	17.7	0.3	17.0	18.1
	Headline height (m)	48	1.9	0.2	1.4	2.3
	Warp tension (MT.)	6	9.9	1.5	7.8	11.5
Physical modeling *(i.e., door spreads were constrained at desired distances*)	Door spread (m)	30	57.5	8.6	45.0	70.0
	Wing spread (m)	30	19.0	1.7	15.8	21.5
	Headline height (m)	30	4.1	0.5	3.5	4.9
	Bridle tension (MT.)	30	5.8	0.1	5.6	6.1
Full-scale observations *(2011 fall multi-species survey aboard the CCGS Teleost)*	Towing depth (m)	48	559.7	396.9	139.0	1422.0
	Door spread (m)	48	59.0	3.9	52.5	65.9
	Wing spread (m)	48	18.6	0.7	17.3	19.8
	Headline height (m)	48	3.5	0.2	3.1	4.2
	Warp tension (MT.)	6	14.3	2.3	11.0	16.9

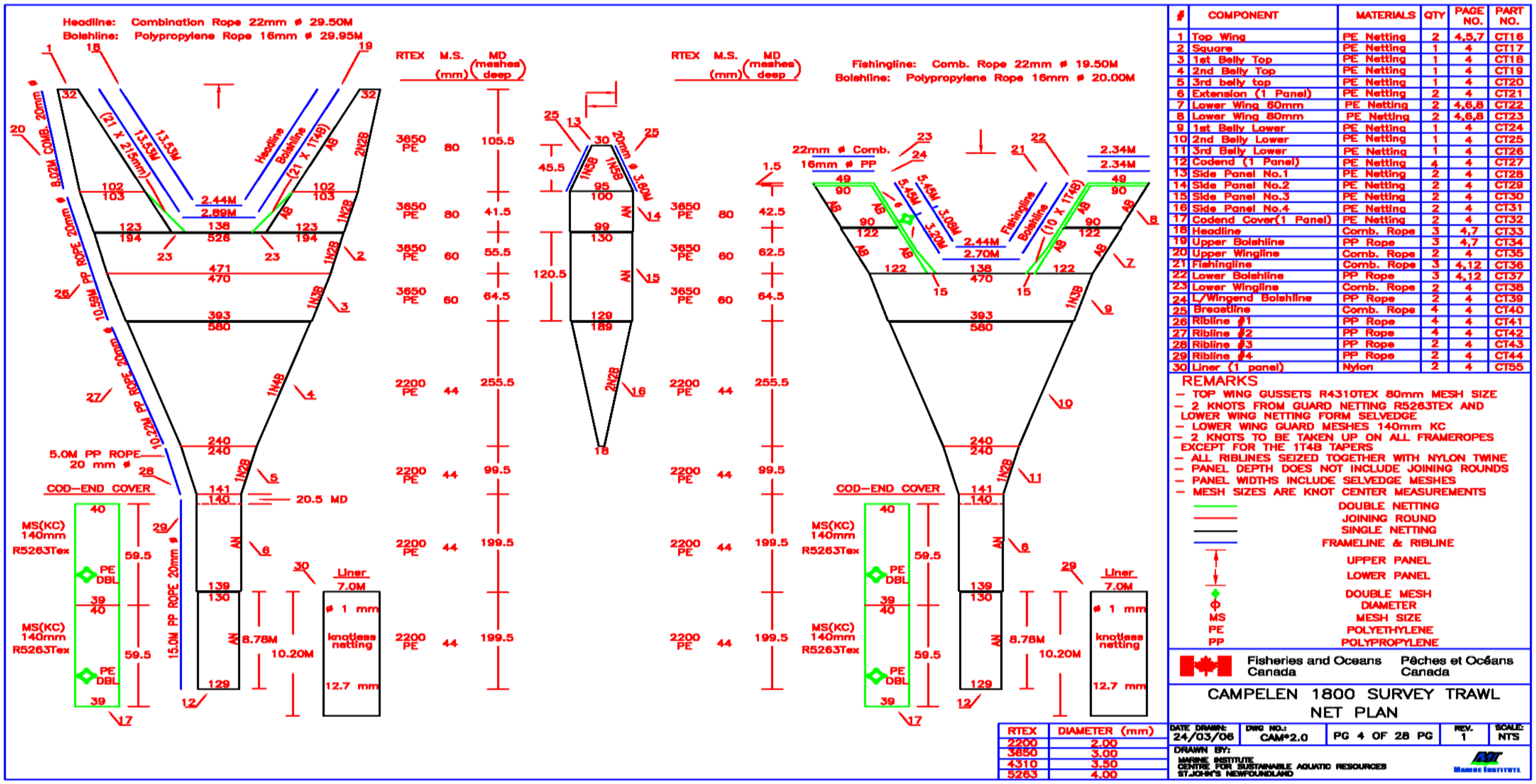
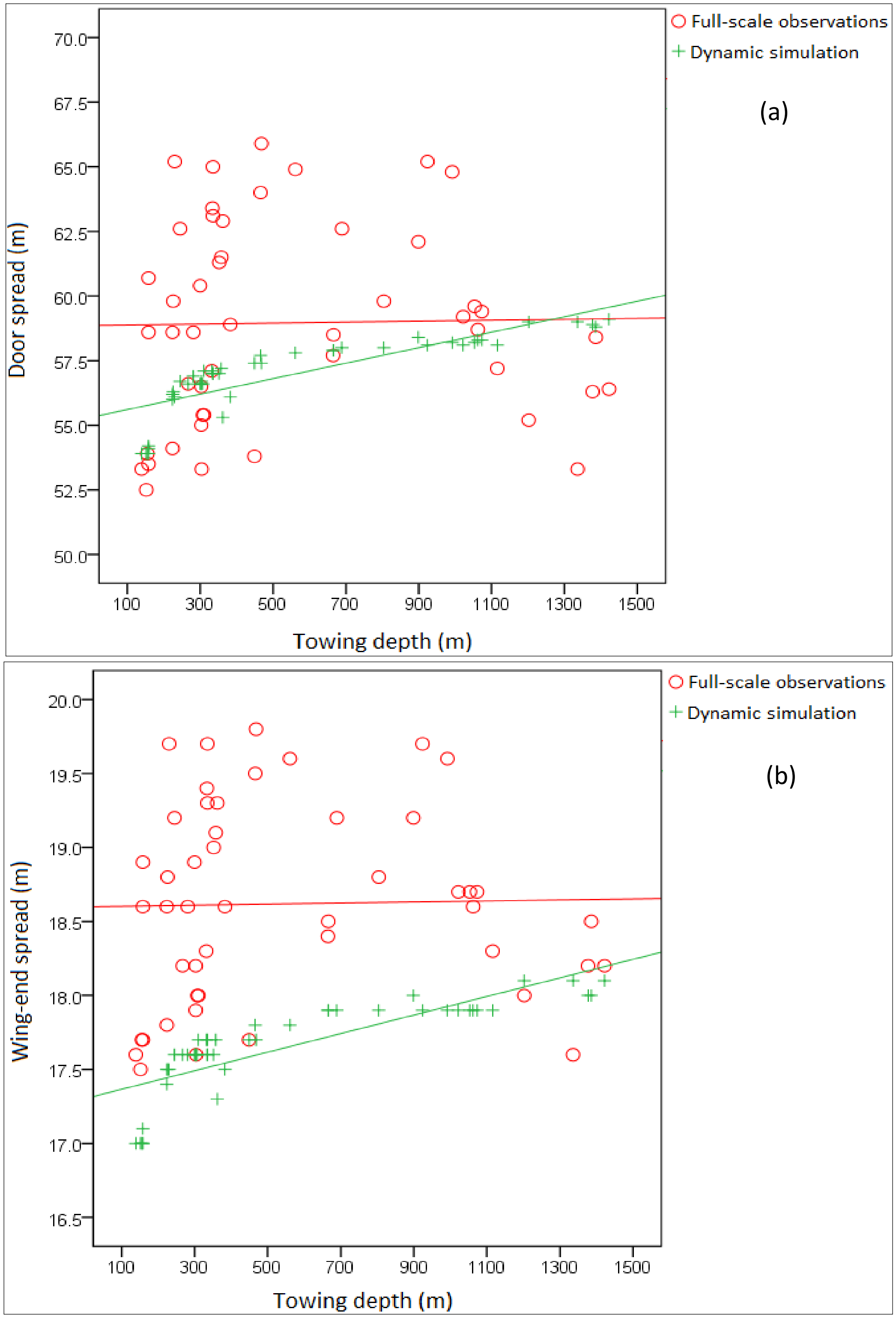


Figure 4.1: Schematic netplan of the Campelen 1800 demersal survey trawl. See Walsh et al. (2009) for additional drawings.


Full-scale observations
Dynamic simulation
(a)
Door spread (m)
70.0
67.5
65.0
62.5
60.0
57.5
55.0
52.5
50.0
100
300
500
700
900
1100
1300
1500
Towing depth (m)
Full-scale observations
Dynamic simulation
(b)
Wing-end spread (m)
20.0
19.5
19.0
18.5
18.0
17.5
17.0
16.5
100
300
500
700
900
1100
1300
1500
Towing depth (m)

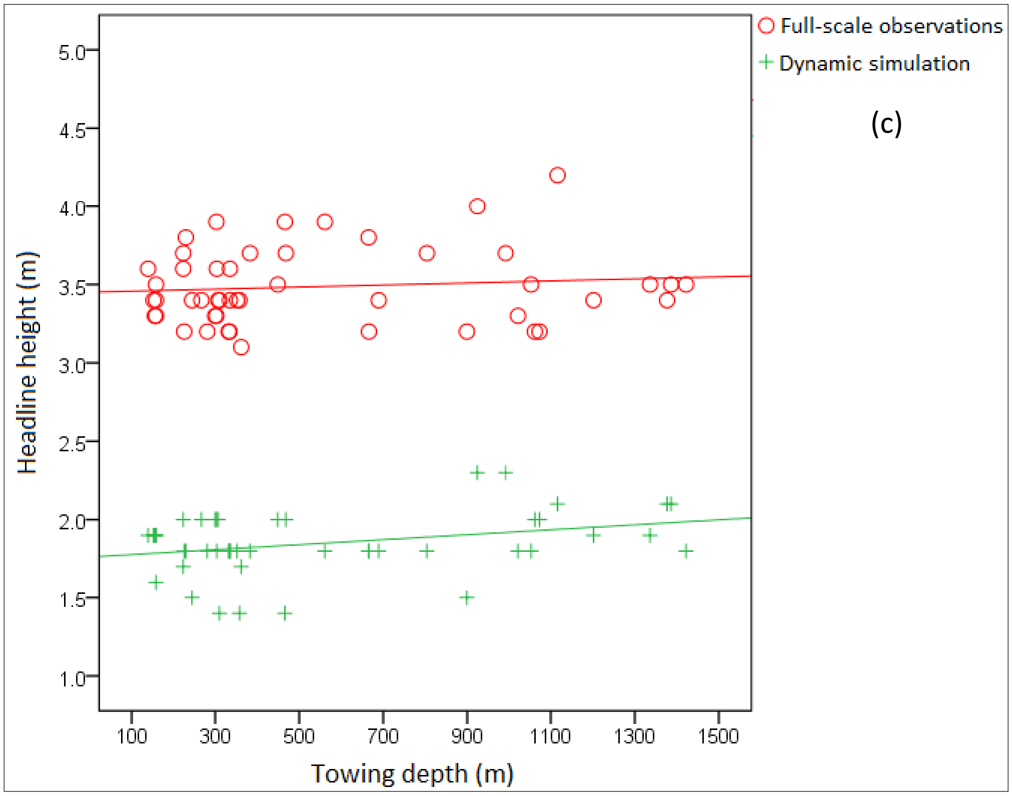


Figure 4.2: Relationships observed between door spread and towing depth (a); wing spread and towing depth (b); and headline height and towing depth (c). The plots show the experimental data collected with dynamic simulation (plus), full-scale observations at sea (open circle). The best fit regression lines are shown for each scatter plot.

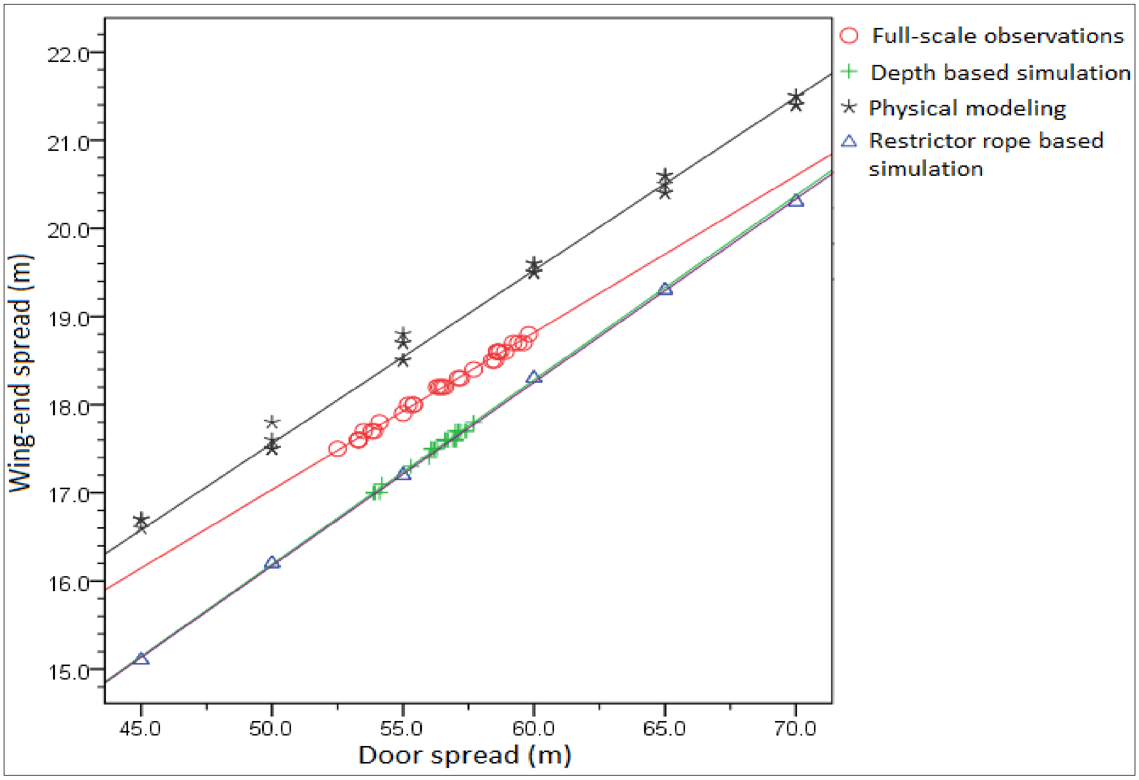


Figure 4.3: Relationships observed between wing-end spread with respect to door spread. The plots show the experimental data collected with depth based dynamic simulation (plus), full-scale observations at sea (open circle), restrictor rope based dynamic simulation (triangle), and physical modeling (star). The best fit regression lines are shown for each scatter plot.

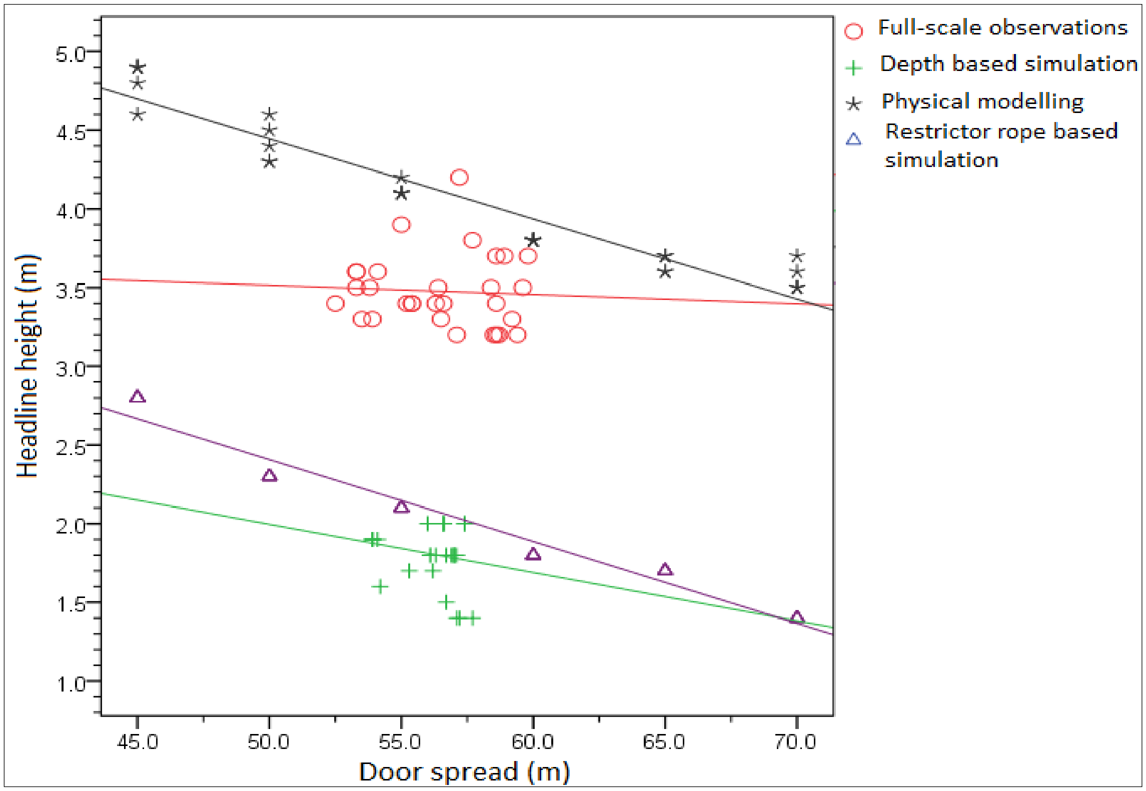


Figure 4.4: Relationships observed between headline height with respect to door spread. The plots show the experimental data collected with depth based dynamic simulation (plus), full-scale observations at sea (open circle), restrictor rope based dynamic simulation (triangle), and physical modeling (star). The best fit regression lines are shown for each scatter plot.

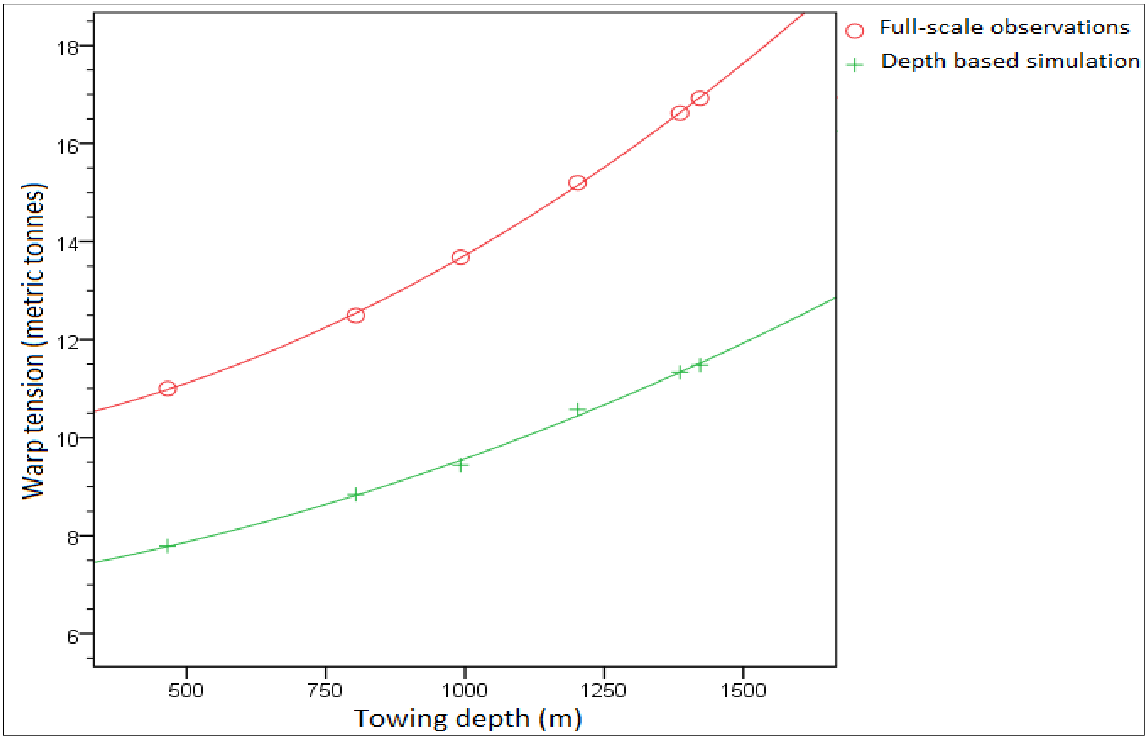
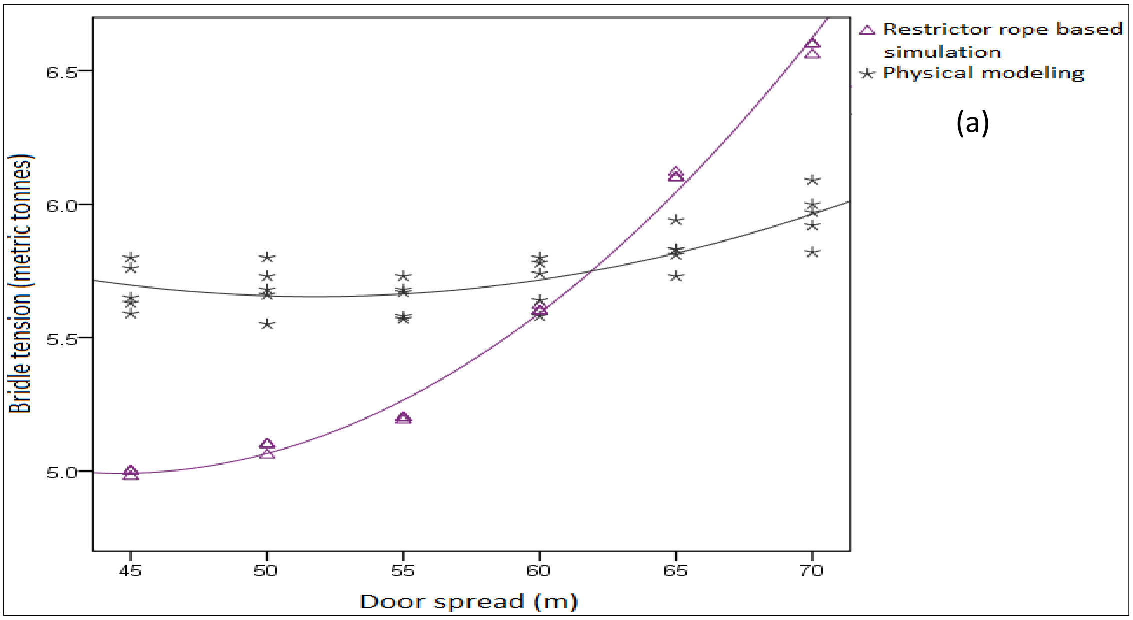


Figure 4.5: Relationships observed between warp tension with respect to towing depth. The plots show the experimental data collected with depth based dynamic simulation (plus) and full-scale observations at sea (open circle). The best fit regression lines are shown for each scatter plot.



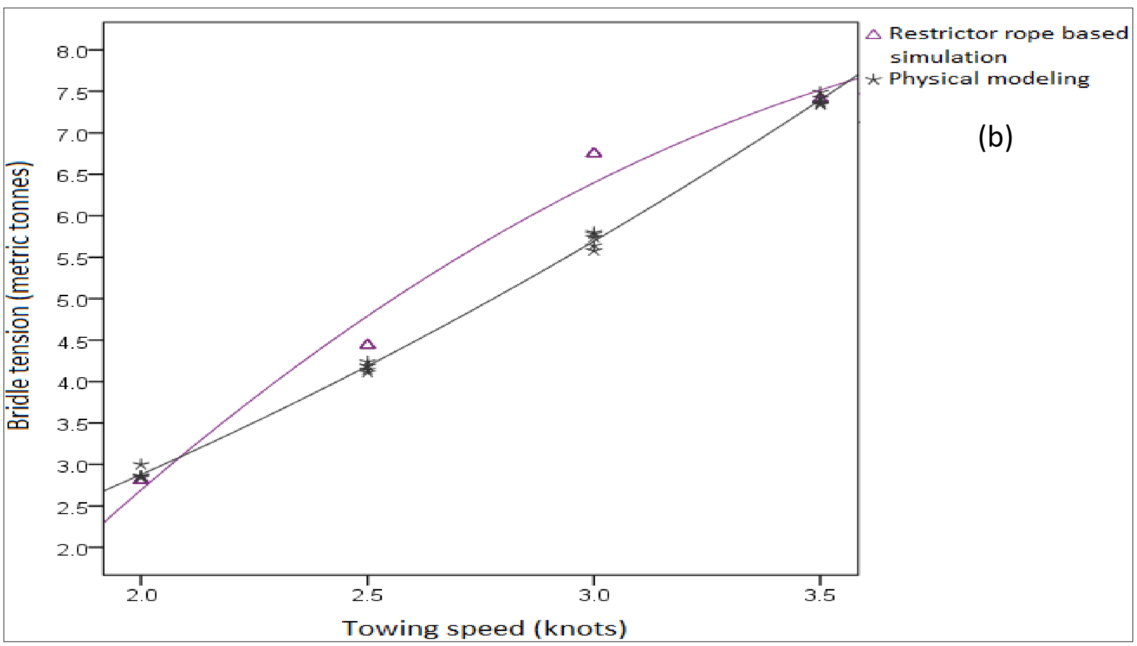


Figure 4.6: Relationships observed between bridle tension and door spread (a); bridle tension and towing speed (b). The plots show the experimental data collected with dynamic simulation (triangle), and physical modeling (star). The best fit regression lines are shown for each scatter plot.

Chapter 5. Assessing the effectiveness of drop chain footgear at reducing bottom contact in the Newfoundland and Labrador shrimp trawl fishery

5.1 Abstract

This study compared the effectiveness of a reduced seabed impact footgear versus a traditional rockhopper footgear on identical bottom trawls targeting northern shrimp (*Pandalus borealis*) in Newfoundland and Labrador, Canada. The experimental trawl used in this study was designed to be low seabed impact through the reduction of contact area of the footgear by replacing traditional heavy rockhopper footgear with only a few drop chains lightly in contact with the seabed (i.e., drop chain footgear). Two variants of the experimental drop chain footgear (9-drop chain and 5-drop chain) were designed, evaluated in a flume tank to estimate contact area with the seabed, and then briefly tested at sea for engineering performance and catchability. Results from the flume tank tests were encouraging, demonstrating that the traditional and experimental trawls were similar in performance, but with the experimental drop chain footgears producing substantial reductions in the predicted contact area with the seabed. Comparative commercial fishing trials were then subsequently made with a total of five pairs of tows (10 tows) for the 9-drop chain and six pairs of tows (12 tows) for the 5-drop chain. Though only briefly tested at sea, the results revealed that the drop chain footgears were promising in both engineering, but less so in the catch of target species. Underwater video observations demonstrated that the drop chain trawling system, with greatly reduced bottom contact on the seabed, could help reduce potential disturbance of marine ecosystems, in particular minimizing encounters with snow crab (*Chionoecetes opilio*).

5.2 Introduction

Concerns over the impact of fishing practices on the ocean environment have been expressed at the local, national, and international scale (Morgan and Chuenpagdee, 2003; Rice, 2006; Fuller et al., 2008). The entire global seafood industry is facing public pressure to amend its fishing practices, particularly bottom trawling, in an effort to reduce bycatch and negative impacts on the seabed. Evidence although at times ambiguous that towed fishing gears harm benthic organisms, reduce habitat complexity, and reduce biodiversity has appeared in scientific literature (Kaiser et al., 2003; Valdemarsen and Suuronen, 2003; Valdemarsen et al., 2007; He and Winger, 2010; Pham et al., 2014) and popular media with increasing frequency (Gilkinson et al., 2006). Current consumer trends and the growing demand for certification by eco-labels such as the Marine Stewardship Council indicate that the public is increasingly concerned with the environmental footprint of fisheries, particularly for bottom trawling. While physical alterations of the seabed by bottom trawling and dredging are evident (e.g., Jones, 1992; Løkkeborg, 2005; Rice, 2006; He and Winger, 2010), the effect of the alterations on the benthic organisms and recovery rates associated with gear alterations depend on substrate type, depth, and natural disturbance in the area.

The northern shrimp (*Pandalus borealis*) and snow crab (*Chionoecetes opilio*) fisheries are important contributors to the local economy of the province of Newfoundland and Labrador, Canada (DFA, 2014). However, snow crab and shrimp fishing grounds are known to overlap considerably from the southern Labrador shelf to the northern Grand Bank, particularly in northern regions such as Northwest Atlantic

Fisheries Organization (NAFO) Divisions 3KL (Dawe et al., 2007). Recent underwater video camera observations of snow crab encountering the traditional footgear (i.e., rockhopper) of a shrimp trawl demonstrated that snow crab are quickly overtaken by the trawl, with approximately 54% of individuals observed confirmed to experience an encounter with the footgear (Nguyen et al., 2014). Rose et al. (2013) demonstrated that the mortality of decapod crabs in response to such encounters with trawl footgear can range from 10-31% depending on the species and region of the footgear they encounter. Subsequent work by Hammond et al. (2013) showed that simple modifications to trawl footgear (i.e., rubber disk footgear with off-bottom sweeps/bridles) achieved a 36% and 50% reduction in mortality levels for Tanner crab (*Chionoecetes bairdi*) and snow crab (*C. opilio*), respectively. These findings suggest that minimizing potentially negative encounters through the use of trawl modifications is a valuable research agenda as it can promote stock productivity through the reduction of unaccounted fishing mortality.

The primary objective of this study was to examine the effectiveness of a novel footgear for reducing the seabed impacts of shrimp trawls off the east coast of Newfoundland and Labrador, Canada. This footgear, referred to as a drop chain footgear, consists of only a few drop chains in contact with the seabed. The use of drop chain footgear technology has been previously investigated or adopted in different fisheries in Australia (Ramm et al., 1993 and Brewer et al., 1996) and the United States (Hannah and Jones, 2000; Pol, 2003; Sheppard et al., 2004). In this study we conducted two comparative fishing experiments, evaluating catch rates of target and non-target species, trawl geometry, fuel consumption, and trawling resistance (i.e., warp tension) to determine the differences between the traditional and experimental trawls (i.e., rockhopper vs. drop chain).

5.3 Materials and Methods

5.3.1 Fishing Gear

In the current study, the trawl design used for the traditional (control) and experimental trawls was the 4-seam, Vónin 2007-1570 shrimp trawl with 33.8 m headline and 32.9 m fishing line (Figure 5.1 a). The traditional and experimental trawls were identical in every way, except for modifications to the footgear and four fewer floats on the fishing line of the experimental trawl. The traditional trawl was rigged with a 32.9 m rockhopper footgear commonly used throughout the fishing fleet. The rockhopper footgear, with a weight of 354 kg, is constructed from different components including wires, travel chains, spacers, bobbins, and rubber discs/wheels. This consisted of 28 rockhopper disks with a diameter of 356 mm, 38 disks with a diameter of 305 mm, and two 356 mm diameter steel bobbins linked together by a 13 mm long-link footgear chain, a 10 mm long-link travel chain, and a 10 mm long-link weight chain (Figure 5.1 b). Flotation was provided using 203 mm trawl floats, with 100 floats on the headline, 18 floats on the fishing line, and five floats on each of the upper selvedges. The trawls were constructed with 25-100 mm mesh and were equipped with two 5.0 m^2 Injector Scorpion steel trawl doors (1,350 kg each) made by Injector Door Limited™ and high-density polyethylene Nordmøre grids.

We tested two experimental footgear designs; the 9-drop chain and 5-drop chain. Both drop chain footgear arrangements were devoid of all rockhopper components and consisted of nine or five drop chains spaced from wing to wing. Each chain was 1.0 m in length, 25.6 kg in weight, and was constructed of 22 mm long-link steel chain (Figure 5.1 c). The total footgear weight of the 9-drop chain and 5-drop chain was 334 and 223 kg, respectively. This weight included the weight of a secondary fishing line which was a combination of chains, spacers, and 100 mm diameter of rubber disks and attached directly to the original fishing line by quick links (Figure 5.1 c).

Scaled engineering models (1:8) of both the traditional and experimental trawls were constructed and evaluated using a flume tank (Winger et al., 2006). The percentage of contact area with the seabed was estimated visually by filming the models while under test in the flume tank.

5.3.2 Comparative Fishing Experiments

Prior to sea trials, we followed the quality-control protocol outlined in DFO (1998) to ensure the trawl nets did not differ in size or shape, with the exception of the footgear (i.e., rockhopper vs. drop chain). The comparative fishing experiments were conducted aboard the F/V *Nautical Legend*, a 20 m commercial trawler, from July 25 to August 1, 2014. Fishing experiments were conducted on the northeast coast (i.e., NAFO Division 3K) of Newfoundland, Canada, with average water depths ranging from 357-390 m (Figure 5.2).

Prior to the comparative fishing experiments, we conducted engineering trials with an opened cod-end. This was to verify that all instrumentation and equipment used to monitor trawl performance, geometry, resistance, and footgear rigging were functioning properly.

We conducted two separate fishing experiments. Experiment 1 consisted of a comparison of the traditional footgear trawl against the experimental 9-drop chain footgear trawl. A total of 10 tows (five pairs) were successfully carried out and included in the analysis. Experiment 2 consisted of a comparison of the traditional footgear trawl against the experimental 5-drop chain footgear trawl. A total of 12 tows (six pairs) was successfully carried out and included in the analysis. The alternate tow method (DFO, 1998) was used to compare catches among paired tows. Paired tows were fished in the same direction to minimize variation in environmental conditions. The warp length was appropriately adjusted for the experimental 5-drop chain footgear trawl to maintain a stable footgear contact with the bottom. Towing speed was approximately 2.3 knots and towing order followed the ABBA-BAAB protocol (DeAlteris and Castro, 1991). ABBA-BAAB protocol is a comparative study by which a control net and experimental net are fished and compared using an alternating, paired methodology. In this case, A = control/traditional net; B = experimental gear). Tow duration varied between one and two hours.

5.3.3 Data Collection and Analysis

Trawl monitoring equipment, including a combination of E-Sonar™ and Netmind™ technology, was used to record measurements of trawl net geometry during sea trials. Trawl geometry parameters measured included door spread (m), wing spread (m), and headline height (m). Hand-held tension meters (i.e., VTM 502 10K developed by Cooper Instruments & Systems) were installed on the warps aft of the winches to measure warp tension (kilogram-force, kgf) for both trawl types. Vessel fuel consumption (L h^{-1}) was also documented for each tow using the vessel's fuel meter located on the bridge. Differences in engineering trawl performance (i.e., trawl geometry, resistance/warp tension) and fuel consumption between the traditional rockhopper and experimental drop chain footgear trawls were compared using paired *t*-tests.

The number of bags of shrimp captured from each tow, with an average weight of 13.6 kg per bag, was recorded. These data were used to compare the differences in catch rates of shrimp (kg min^{-1}) caught by the traditional and experimental footgear trawls using paired *t*-tests. Power analysis was performed to determine the statistical power and the extent to which the proposed sample size (number of paired tow comparisons for our future experiments) would be adequate to detect the differences in the catch rates of shrimp between the experimental and traditional trawls. We based our power calculations on the assumption of power level (0.95), significant level (0.05), and the population effect size as obtained in the current study. Sub-samples of shrimp were also taken back to the laboratory to estimate the number of individuals per kg (an assessment of average body size).

For each tow, the number and cumulative weight of each major fish species representing at least 2.5% of total catch captured incidentally (bycatch) were recorded and individual body lengths were obtained. Miscellaneous bycatch species captured infrequently and in low abundance were only counted and weighed. Differences in catch rates (numbers per hour, N h^{-1}) of each major bycatch species between the traditional and experimental footgear trawls were analyzed using paired *t*-tests. The proportion of catch at each length class for major bycatch species from the control and experimental trawls was analyzed using the Generalized Linear Mixed Models (GLMM) with fish length as the explanatory variable (fixed effect) and individual tow as the random effect, following the technique described by Holst and Revill (2009).

Underwater video footage was recorded during the experiments using a low-light TrawlCamera manufactured by JT Electric. The camera was attached to the fishing line of the trawl in the manner similar to Nguyen et al. (2014) (see also Chapter 2). The video footage was used to determine the performance of the drop chain footgear relative to the seabed and its herding effects on shrimp and bycatch species; in particular, the interaction or encounter of snow crab with the drop chains.

All of the statistical procedures regarding paired *t*-tests were performed using the IBM SPSS Statistics software package. The GLMM was implemented using the glmmPQL function in the MASS package (Venables and Ripley, 2002) of R statistical software (R Development Core Team, 2014), which used a penalized quasi-likelihood approach (Breslow and Clayton, 1993). Statistical power analyses were conducted using G*Power 3.1 (Faul et al., 2009).

5.4 Results

5.4.1 Flume Tank Tests

Results from the flume tank testing demonstrated that the traditional and experimental trawls were similar in net geometry and performance, but the experimental drop chain footgear trawls had substantial reductions in contact area with the seabed, as expected. The footgear (rockhopper) of the traditional trawl consisted of 68 contact points with the seabed (Figure 5.3 a). This produced a footprint that made contact with an estimated 69% of the seabed in the path of the trawl. The experimental footgear (9-drop chain and 5-drop chain) (Figures 5.3 b and c) produced footprints that made contact with only 11 and 6%, respectively, of the seabed in the path of the trawl.

5.4.2 Engineering Trawl Performance

Mean door spread, wing spread, and headline height recorded in Experiment 1 were significantly different between the experimental trawl (9-drop chain footgear) and the traditional rockhopper footgear trawl, but the differences were generally less than 10% (Table 5.1). Whereas, the warp tension (kgf) and fuel consumption (L h^{-1}) were not significantly different between the trawl types (Table 5.1). In Experiment 2, mean door spread of the experimental trawl with 5-drop chains was on average 4% higher than that recorded for the traditional footgear trawl and this difference was statistically significant (Table 5.1). Mean wing spread, headline height, warp tension and fuel consumption were not significantly different between the experimental and traditional footgear trawls in Experiment 2 (Table 5.1).

We observed some unexpected technical challenges during fishing operations for the experimental footgear trawls. On two occasions the trawl net body of the experimental 9-drop chain trawl was damaged resulting in significant tears in the netting of the first and second side panels. Repairs were completed at sea and fishing operations were resumed. An operational issue regarding the drop chains causing tangles during the trawl shooting away or hauling back was also observed.

5.4.3 Catch Comparison Results

- ***Shrimp catch***

In Experiment 1, there was no difference in the mean catch rate for shrimp between the traditional footgear trawl and experimental 9 drop-chain trawl (t-statistic=0.646, df=4, p=0.553) (Table 5.2). However, the statistical power to detect this effect was low (0.25) (Table A1 in Appendix) given low number of paired tow comparisons and the highly variable shrimp catch rates observed for the 9-drop chain footgear. For Experiment 2, mean shrimp catch rates decreased approximately 52% from the traditional footgear trawl (6.84 kg min^{-1}) to the experimental 5-drop chain footgear trawl (3.29 kg min^{-1}), and this difference was statistically significant (t-statistic=5.162, df=5, p=0.004) (Table 5.2).

In both experiments, there were no differences in the size of shrimp caught between the traditional and experimental trawls. In Experiment 1, the mean ($\pm$ 1 S.E.) number of shrimp per kilogram was 151.9 $\pm$ 6.27 individuals kg^{-1} in the traditional trawl, and 163.3 $\pm$ 3.10 individuals kg^{-1} in the experimental trawl (t-statistic=1.497, df=21,

p=0.149). In Experiment 2, the numbers of shrimp per kilogram were: 183.9 $\pm$ 2.12 individuals kg^{-1} in the traditional trawl, and 179.2 $\pm$ 3.34 individuals kg^{-1} in the experimental trawl (t-statistic=-1.099, df=32, p=0.280) (Figure 5.4).

- ***Bycatch***

The predominant bycatch species caught by the traditional and experimental footgear trawls was turbot (*Reinhardtius hippoglossoides*), comprising 82.1 and 87.1% of the total bycatch on average by count, respectively (Table 5.3). Atlantic cod (*Gadus morhua*) and American plaice (*Hippoglossoides platessoides*) were also frequently caught by both the experimental and traditional trawls. These species accounted for 10.1 and 3.6% of the total bycatch on average respectively for the traditional footgear trawl, 4.8 and 3.9% respectively for the experimental 9-drop chain footgear trawl, and 6.4 and 2.6 % respectively for the experimental 5-drop chain footgear trawl (Table 5.3). In Experiment 1, differences in the mean catch rates (numbers per hour) of major bycatch species were generally less than 10% between the traditional footgear trawl and experimental 9-drop chain footgear trawl and these differences were not statistically significant (Table 5.2). The observed proportions at length of the total catches of each of the major bycatch species in the experimental 9-drop chain footgear trawl were found to be independent of fish length, owing to the fact that length was not a significant factor in the curve fitting of the GLMM procedure (Table 5.4, Figure 5.5). In Experiment 2, the experimental 5-drop chain footgear trawl had statistically lower bycatch catch rates for American plaice (69.1%) compared to the traditional trawl rigged with rockhopper footgear (*t*-statistic=2.834, df=5, *p*=0.036). The experimental 5-drop chain footgear trawl produced a lower average catch of cod (22 vs. 73) and turbot (297 vs. 394) but neither difference was statistically significant (cod: *t*-statistic=1.392, df=5, *p=0.223;* turbot: *t*-statistic=2.039, df=5, *p*=0.097) (Table 5.2). The results from the GLMM analyses showed that the experimental trawl (5 drop-chain footgear) was less efficient in catching turbot, Atlantic cod, and American plaice (Table 5.4 and Figure 5.6). The relative efficiency of the experimental trawl was approximately 0.10 to 0.50, depending on fish length. For Atlantic cod and American plaice, the shape of the curve (i.e., bowl shaped) indicates that the experimental trawl was less efficient at catching fish in the middle of the size distribution but was nearly equal to the traditional trawl for fish at the ends of the distribution (i.e., very small and very large fish).

Miscellaneous bycatch species captured infrequently by the traditional and experimental footgear trawls accounted for approximately 4.6% of the total bycatch (Table 5.3). Differences in overall mean catch rates of miscellaneous species were not statistically significant (Table 5.2).

- ***Underwater observations***

A total of 125 minutes of underwater video was recorded on the experimental 9-drop chain footgear in Experiment 1, but only 60 minutes of video was usable for analysis; the rest was too cloudy or the trawl was not on bottom. Video observations revealed the drop chain, which was attached directly to the secondary fishing line at the centre of the footgear, was in stable contact with the seabed. Shrimp, snow crab, American plaice, and turbot were observed distributed near or on the seabed (Figure 5.7). A total of 64 crabs were observed. In all cases, snow crab easily passed under the fishing line of the experimental trawl and out of the path of capture (see video in Appendix). The majority (92%) of the crabs observed had no direct encounters (i.e., collisions) with the drop chain (i.e., went under fishing line and between the drop chains). The remaining 8% came into contact with the chain.

5.5 Discussion

Results from our flume tank testing and comparative fishing experiments demonstrated the promising engineering features of drop chain footgears. Compared to the traditional bottom trawl equipped with rockhopper footgear, we found that experimental trawls equipped with drop chain footgears had substantial reductions in the predicted contact area with the seabed and only minor differences in trawl geometry and resistance.

One of our interesting findings was that both of the experimental footgear trawls had a greater mean door spread and wing spread compared to the traditional trawl. With this additional spread came a corresponding reduction in headline height, which is known to have an inverse linear relationship with door spread and wing spread (Godø and Engås, 1989). Such trawl geometry differences were unexpected results as the trawls were the same design, with the exception of the footgear components (drop chain vs. rockhopper). In addition, the flume tank testing did not provide evidence for large differences in trawl geometry. Previous authors have suggested that increased horizontal opening should result in increased catch rate of shrimp (SINTEF, 2004 and Munden et al., 2013); however, this effect was not observed in this study. Functional explanations for why the drop chain trawls experienced greater spread during sea trials are speculative at this point. We hypothesize that the removal of the large rockhopper footgear may have reduced friction with the seabed, which reduced the inward pull on the doors and wings, allowing them to spread to a greater extent.

Our results revealed that the catch rate for shrimp by the experimental 9-drop chain footgear trawl used in Experiment 1 was not significantly different from the catch rates of the traditional rockhopper footgear trawl, despite a mean difference of 23%. This non-significant finding may be explained by the highly variable shrimp catch rates observed at sea together with the low number of paired tows, which led to low statistical power necessary for detecting a difference. Therefore, further commercial fishing trials are recommended to provide sufficient paired tows (30-40 paired comparisons, see Table A1 in Appendix) for demonstrating whether the real-world differences in shrimp catch rates between experimental and traditional trawls are statistically different.

Our underwater video observations revealed that shrimp and bycatch species were distributed near the seabed, providing easy opportunity for escape underneath the fishing line and between the drop chains (see video in Appendix). While this study did not measure the height of the fishing line off the seabed under fishing conditions, previous studies have shown that this parameter can significantly affect the overall catchability of shrimp and bycatch species (Beardsley, 1973; Hannah and Jones, 2003; He et al., 2006;

Hannah et al., 2011; Hannah and Jones, 2013). Given the reduced catch rates of shrimp and bycatch observed in Experiment 2, we hypothesize that reducing the number of chains caused the trawl to operate further from the seabed.

Developing and ultimately implementing footgears with reduced bottom contact remains a desirable goal for stakeholders. One of the primary concerns raised by the fishing industry is their contention that shrimp trawling represents an important source of unaccounted mortality, negatively affecting the snow crab population and habitat (Monty Way, pers. comm.). In a previous study we found about 54% of the crabs observed were confirmed to experience an encounter with the rockhopper (either disks or spacer/chain) (see Nguyen et al., 2014; Chapter 2 herein). By contrast, our trawl-mounted video camera observations in this study demonstrated that, at least around a single drop chain, only 8% of the crabs observed were found to experience an encounter with the drop chain. This suggests that the likelihood of snow crab mortality in relation with drop chains is expected to be low or minimized. Admittedly, these video observations were focused only on the centre of the footgear (one drop chain was in the field of view) thus limiting our ability to evaluate interactions in other regions of the trawl.

Assessing any fishing gear requires that researchers study the impact of the gear on target and non-target species, as well as the practicality of the gear for use in a fishery. While our study focused on the former, we did identify several pathways for further improvement of this gear. First, the drop-chain-equipped trawl net experienced two tear-ups over the course of the study. It is unclear whether these tear-ups were due to the footgear or chance alone. The application of drop chain footgear to reduce bycatch in the ocean shrimp (*Pandalus jordani)* trawl fishery off the west coast of the United States has been investigated and no tear-ups reported (Hannah and Jones, 2000), suggesting that the drop chain footgear is not fundamentally flawed. Second, operational safety issues may exist as crews grow accustomed to using this gear. Specifically, when shooting the gear and during haulback, the drop chains swing off the drum in a manner that could impact fishers on deck. From a safety point of view, it is likely that vessel crew would require a certain period of time to adjust to or become comfortable with the drop chain operations.

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Table 5.1: Tow-by-tow comparison of trawl geometry, trawling resistance and fuel consumption. Mean in meter (m) for door spread, wing spread and headline height, kilogram force for warp tension (kgf) and liter per hour (liter hr-1) for fuel consumption, standard error of the mean (SE), percent change (% change), degrees of freedom (df), *t*-statistic, and *p*-value denoted in bold are statistically significant based on an alpha of 0.05.

	Pair	Door spread		Wing spread		Headline height		Warp tension		Fuel consumption	
		Control	D. chain	Control	D. chain	Control	D. chain	Control	D. chain	Control	D. chain
XPERIMENT 1	1	58.47	58.43	19.16	21.54	5.04	4.70	6945	6793	64.75	67.25
	2	59.52	61.19	19.45	20.87	5.02	4.38	6713	6733	67.13	69.50
	3	59.71	61.97	19.48	na	5.32	4.68	5888	6368	54.38	58.63
	4	58.53	62.28	19.74	21.85	4.87	na	6293	5861	67.75	64.25
	5	58.68	60.75	19.09	21.05	4.79	na	6491	6663	65.62	65.00
	Mean	58.98	60.92	19.36	21.32	5.12	4.58	6466.00	6483.60	63.92	64.93
	SE	0.3	0.7	0.1	0.2	0.1	0.1	180.9	171.9	2.4	1.8
	% change	+3.2		+10.1		-9.4		-0.3		+1.6	
	df	4		3		2		4		4	
	t-statistic	-3.195		-9.734		5.4		-0.115		-0.728	
	p-value	**0.033**		**0.002**		**0.033**		0.914		0.507	
EXPERIMENT 2	6	60.61	62.77	na	21.63	5.16	na	5790	5885	58.00	56.75
	7	60.38	62.9	19.46	21.06	5.13	4.63	5960	5800	56.75	58.00
	8	60.91	63.7	19.48	21.75	5.21	5.06	5580	5450	53.75	50.50
	9	63.48	65.97	20.37	23.25	5.13	na	5735	5900	52.25	53.25
	10	60.84	63.55	20.06	na	na	na	6185	6085	63.50	65.25
	11	61.61	64.72	19.96	22.61	na	na	6245	6030	55.75	55.00
	Mean	61.31	63.94	19.87	22.06	5.16	4.85	5915.83	5858.33	56.67	56.46
	SE	0.5	0.5	0.2	0.4	0.0	0.2	107.1	91.9	1.6	2.1
	% change	+4.3		+11.0		-6.1		-1.0		-0.4	
	df	5		5		1		5		5	
	t-statistic	-20.073		-0.339		1.857		0.928		0.269	
	p-value	**0.000**		0.748		0.314		0.396		0.799	

Note: *na is meant the data was not available as the sensors were communicate improperly.*

Table 5.2: Tow-by-tow comparison of N. shrimp, major bycatch species and miscellaneous species. Total catch mean in kilogram per minute (kg min-1) for N. shrimp, number of individuals per hour (N hr-1) for turbot, Atlantic cod, A. plaice, and miscellaneous species, standard error of the mean (SE), percent change (% change), degrees of freedom (df), *t*-statistic, and *p*-value denoted in bold are statistically significant based on an alpha of 0.05.

	Pair	N. shrimp		Turbot		Atlantic cod		A. plaice		Miscellaneous	
		Control	D. chain	Control	D. chain	Control	D. chain	Control	D. chain	Control	D. chain
EXPERIMENT 1	1	3.29	10.09	85	272	34	1	50	0	60	9
	2	7.03	5.67	143	585	29	24	46	9	23	25
	3	3.74	1.36	246	65	29	77	5	74	16	59
	4	9.53	7.14	838	472	23	27	9	34	33	29
	5	11.11	2.49	1195	1381	50	27	7	3	55	39
	Mean	6.94	5.35	501.40	555.00	33.00	31.20	23.40	24.00	37.40	32.20
	SE	1.5	1.6	219.3	224.8	4.6	12.4	10.1	13.9	8.7	8.3
	% change	-22.9		+10.7		-5.5		+2.6		-13.9	
	df	4		4		4		3		4	
	t-statistic	0.646		-0.371		0.128		-589		0.343	
	p-value	0.553		0.729		0.904		0.597		0.749	
EXPERIMENT 2	6	6.58	2.72	773	445	23	12	17	3	14	32
	7	5.44	1.59	786	664	21	5	5	0	19	22
	8	7.03	1.81	473	481	16	6	6	2	19	8
	9	7.03	3.86	209	129	19	5	4	5	5	3
	10	5.44	4.99	0	20	330	93	24	11	20	5
	11	9.53	4.76	162	34	30	8	25	4	7	19
	Mean	6.84	3.29	393.83	297.17	73.17	21.50	13.50	4.17	14.00	14.83
	SE	0.6	0.6	131.4	110.7	51.4	14.3	4.0	1.5	2.7	4.6
	% change	-51.9		-24.5		-70.6		-69.1		+6.0	
	df	5		5		5		5		5	
	t-statistic	5.162		2.173		1.392		2.834		-0.159	
	p-value	**0.004**		0.082		0.223		**0.036**		0.88	

Table 5.3: Catch composition of non-target species caught by the traditional and experimental footgear trawls.

Species group	Species included	Scientific name	% of total catch
Major bycatch	Turbot	*Reinhardtius hippoglossoides*	82-87
	Atlantic cod	*Gadus morhua*	5-10
	American plaice	*Hippoglossoides platessoides*	2.5-4
Miscellaneous	Redfish	*Sebastes fasciatus*	0.3-0.5
	Capelin	*Mallotus villosus*	0.5-0.7
	Sandlance	*Ammodytes spp.*	1.3-1.7
	Eelpout	*Zoarces spp.*	0.5-0.7
	Sculpin	*Myoxocephalus octodecimspinosus*	0.4-0.6
	Grey sole	*Glyptocephalus cynoglossus*	0.1-0.2
	Alligator fish	*Aspidophoroides monopterygius*	0.1-0.3
	Snow crab	*Chionoecetes opilio*	0.1-0.2
	Wolf fish	*Anarhichas denticulatus*	0.1-0.4
	Skate	*Family rajidae*	0.2-0.4

Table 5.4: Generalized linear mixed model parameters for: turbot, Atlantic cod, and American plaice; where model and parameter are the chosen model (either constant, linear, quadratic, or cubic), estimate is the value of the slope or intercept, SE is the standard error of the mean, df is the degrees of freedom, *t*-statistic, and *p*-value denoted in bold are statistically significant based on an alpha of 0.05.

	Species	Model	Parameter	Estimate	SE	df	*t*-value	*p*-value
EXPERIMENT 1	Turbot	Constant	β_0	0.163	0.468	73	0.348	0.728
	Atlantic cod	Constant	β_0	62.545	32.063	22	1.950	0.063
	A. plaice	Constant	β_0	11.288	6.559	9	1.721	0.119
EXPERIMENT 2	Turbot	Cubic	β_0	-9.524	3.718	69	-2.562	**0.012**
			β_1	1.602	0.667	69	2.215	**0.019**
			β_2	-0.089	0.039	69	-2.090	**0.024**
			β_3	0.001	0.000	69	1.923	**0.035**
	Atlantic cod	Cubic	β_0	41.743	14.551	20	2.869	**0.009**
			β_1	-8.689	3.210	20	-2.706	**0.013**
			β_2	0.568	0.231	20	2.460	**0.023**
			β_3	-0.012	0.005	20	-2.228	**0.037**
	A. plaice	Quadratic	β_0	43.944	10.682	6	4.113	**0.006**
			β_1	-4.451	1.074	6	-4.143	**0.006**
			β_2	0.110	0.026	6	4.115	**0.006**

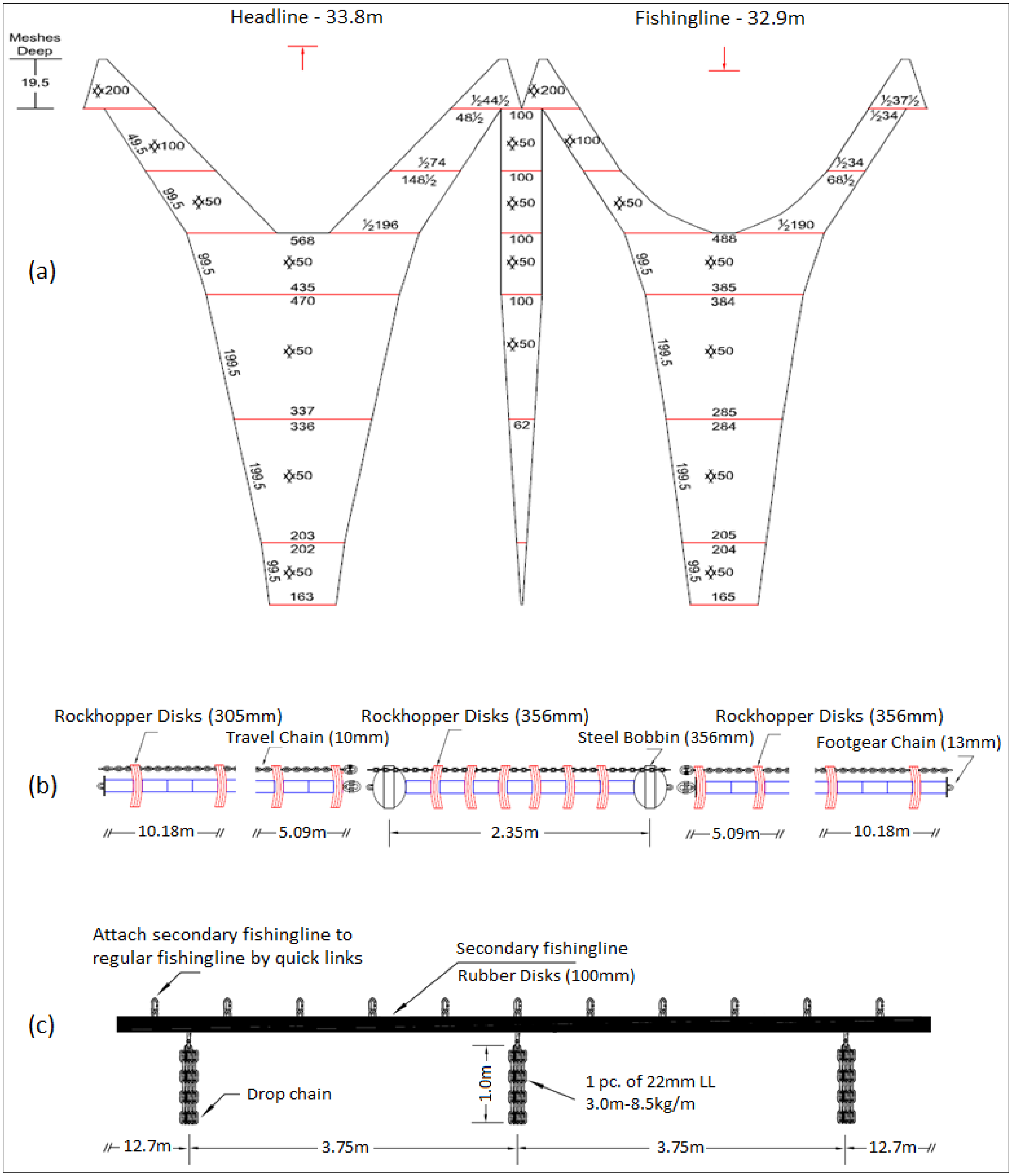

Figure 5.1: Schematic netplan of the Vónin 2007-1570 shrimp trawl (a), rigged with a traditional rockhopper footgear (b), and experimental drop chain footgear (c).

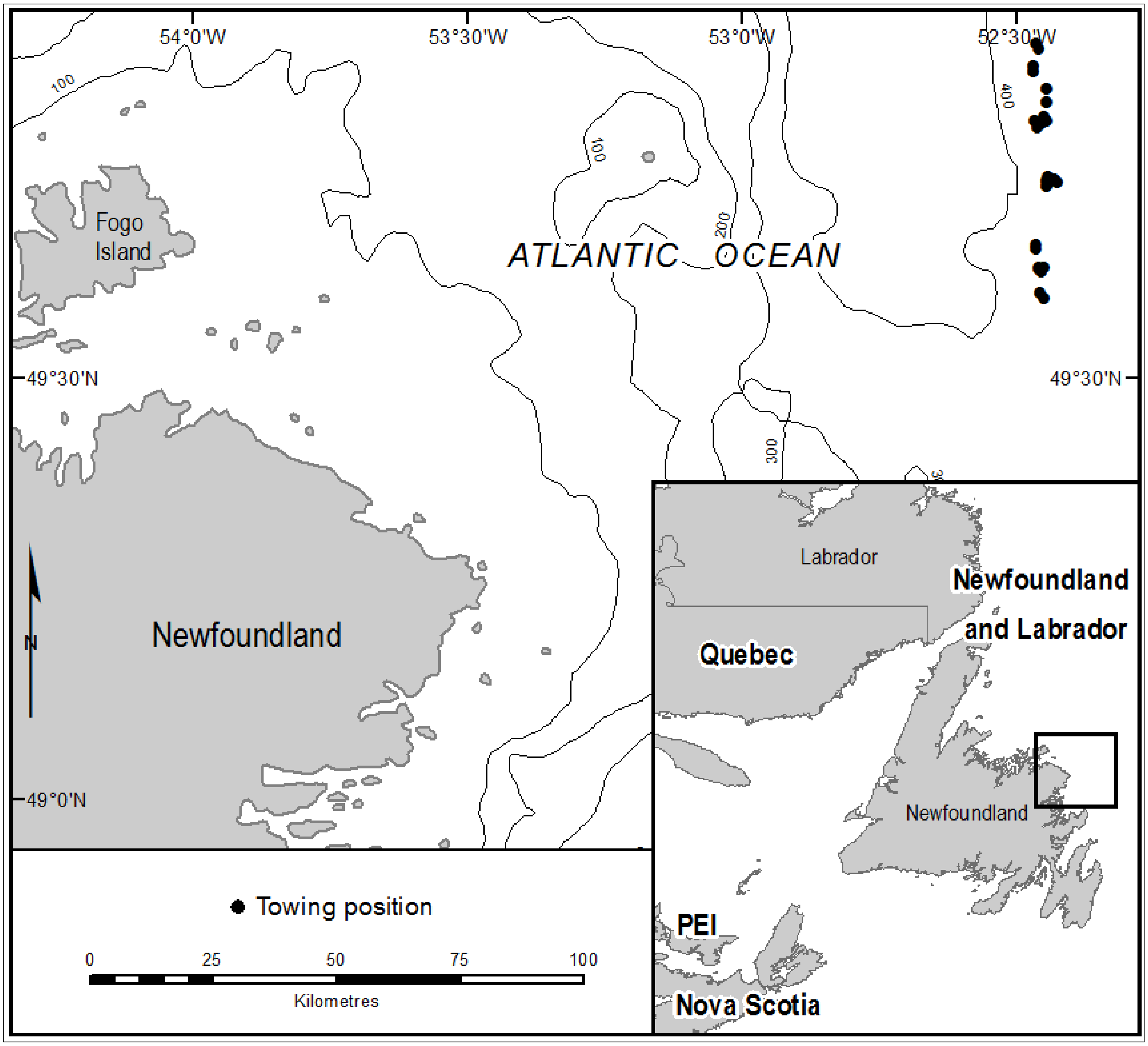

Figure 5.2: The experimental study area in NAFO Division 3K (SFA6) on the northeast coast of Newfoundland, Canada. Black box denotes the towing area.

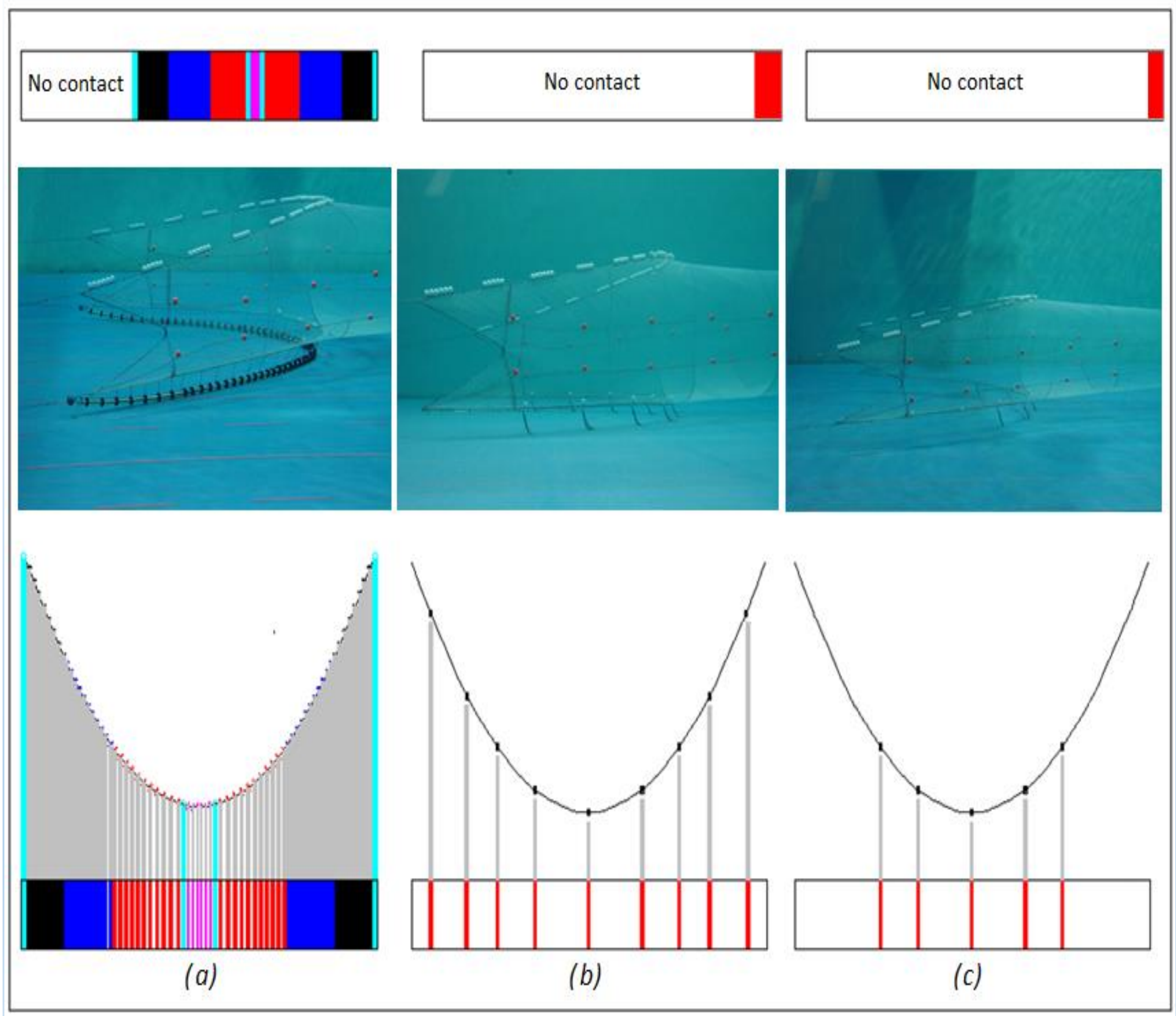

Figure 5.3: Schematic of the estimated percentage of seabed contact for a traditional rockhopper footgear (a), experimental 9-drop chain footgear (b), and experimental 5-drop chain footgear (c). The colour coding of seabed contact is described for different footgear components/sections. For traditional footgear which made 69% of seabed contact: Bobbin (Green), Wingtip sections (Black), Wing sections (Blue), Bunt wing sections (Red), Bosom section (Purple). For experimental footgears which made only 11% (9-drop chain) and 6% (5-drop chain) of seabed contact: Drop chains (Red).

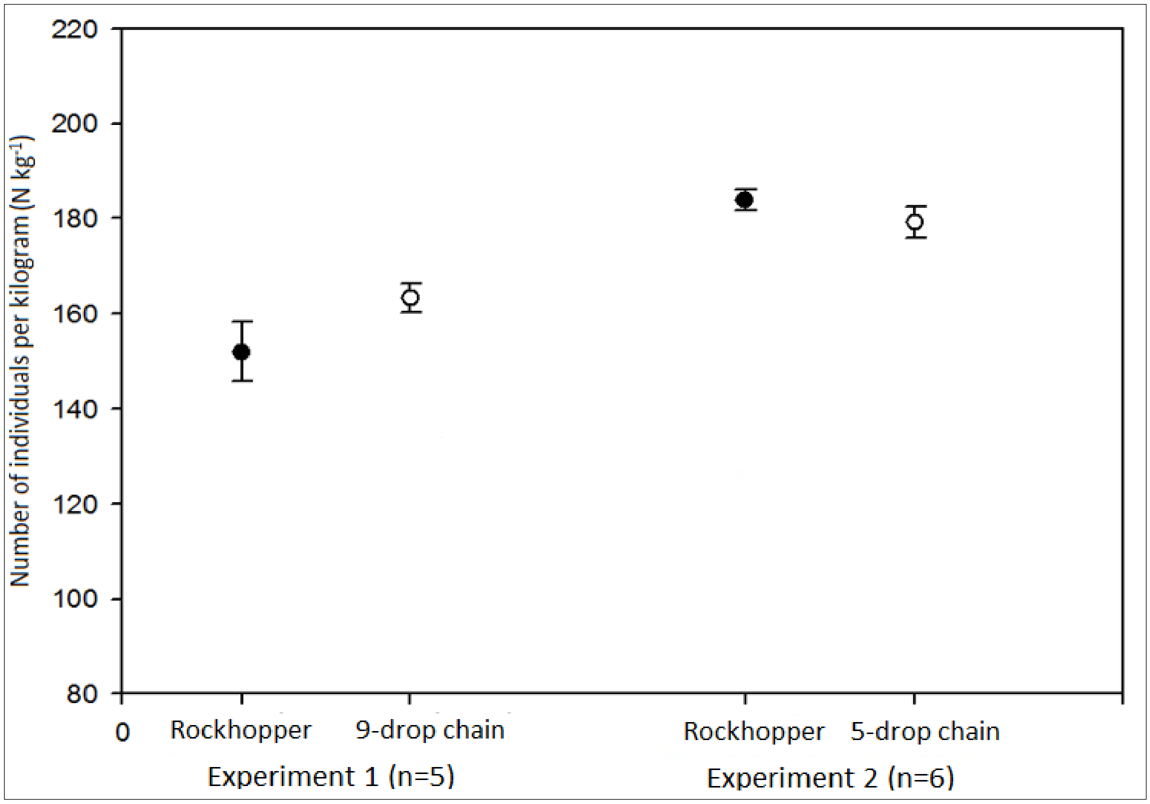

Figure 5.4: Number of individuals per kilogram (N kg-1) for northern shrimp caught by the traditional rockhopper and experimental drop chain footgear trawls. Error bars represent ± 1 S.E.

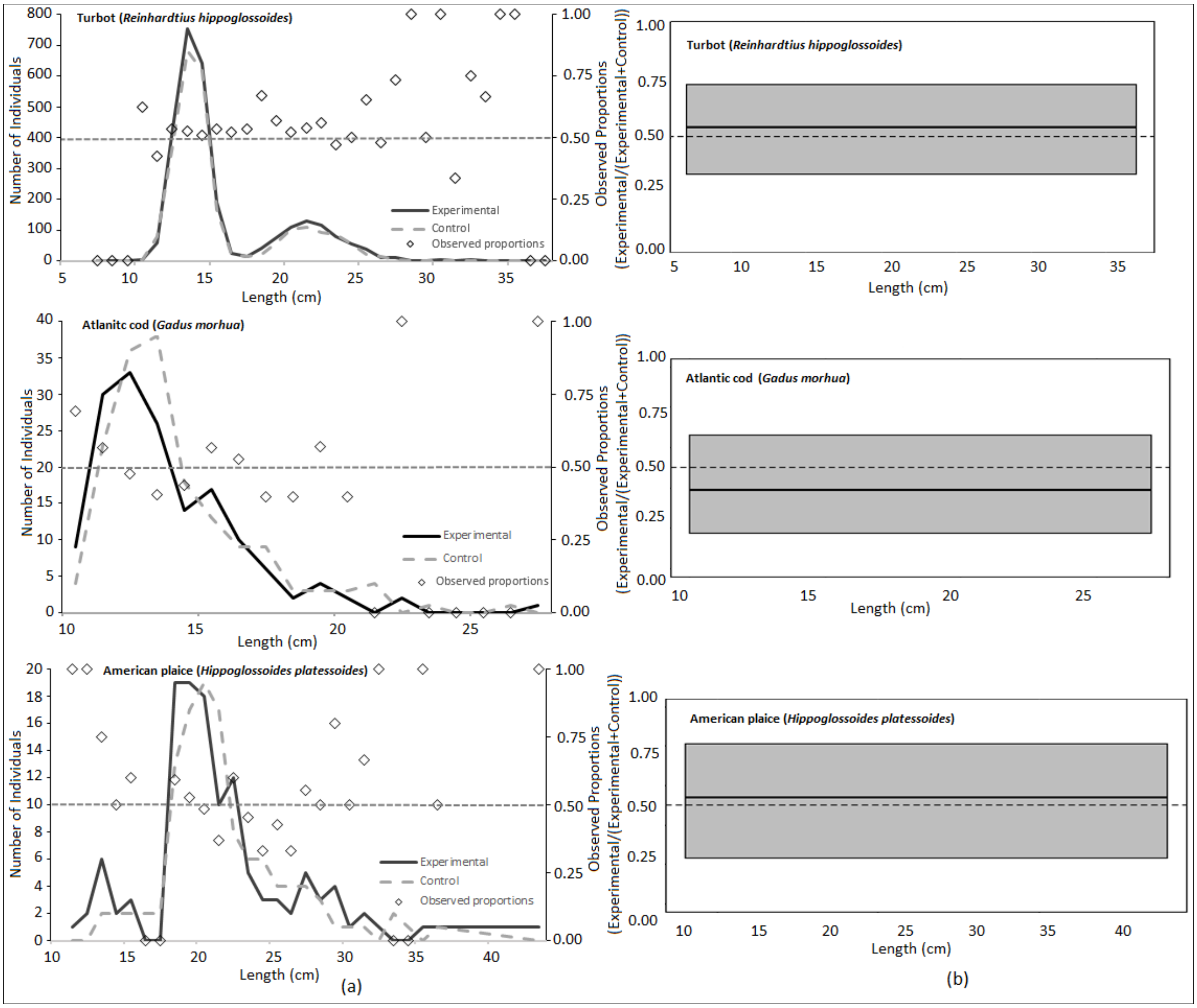

Figure 5.5: Experiment 1-Pooled length frequency and observed proportions (experimental / (experimental + control)) of the total catches caught in the experimental 9-drop chain footgear trawl (a). Generalized linear mixed model (GLMM) modelled proportion of the total catches caught in the experimental 9-drop chain footgear trawl. Interpretation: a value of 0.5 indicates an even split between the two trawls, whereas a value of 0.25 indicates that 25% of the total fish at that length were caught in the drop chain footgear trawl and 75% were caught in the traditional rockhopper footgear trawl. The shaded areas around the mean curves (bold lines) are the 95% confidence regions (b).

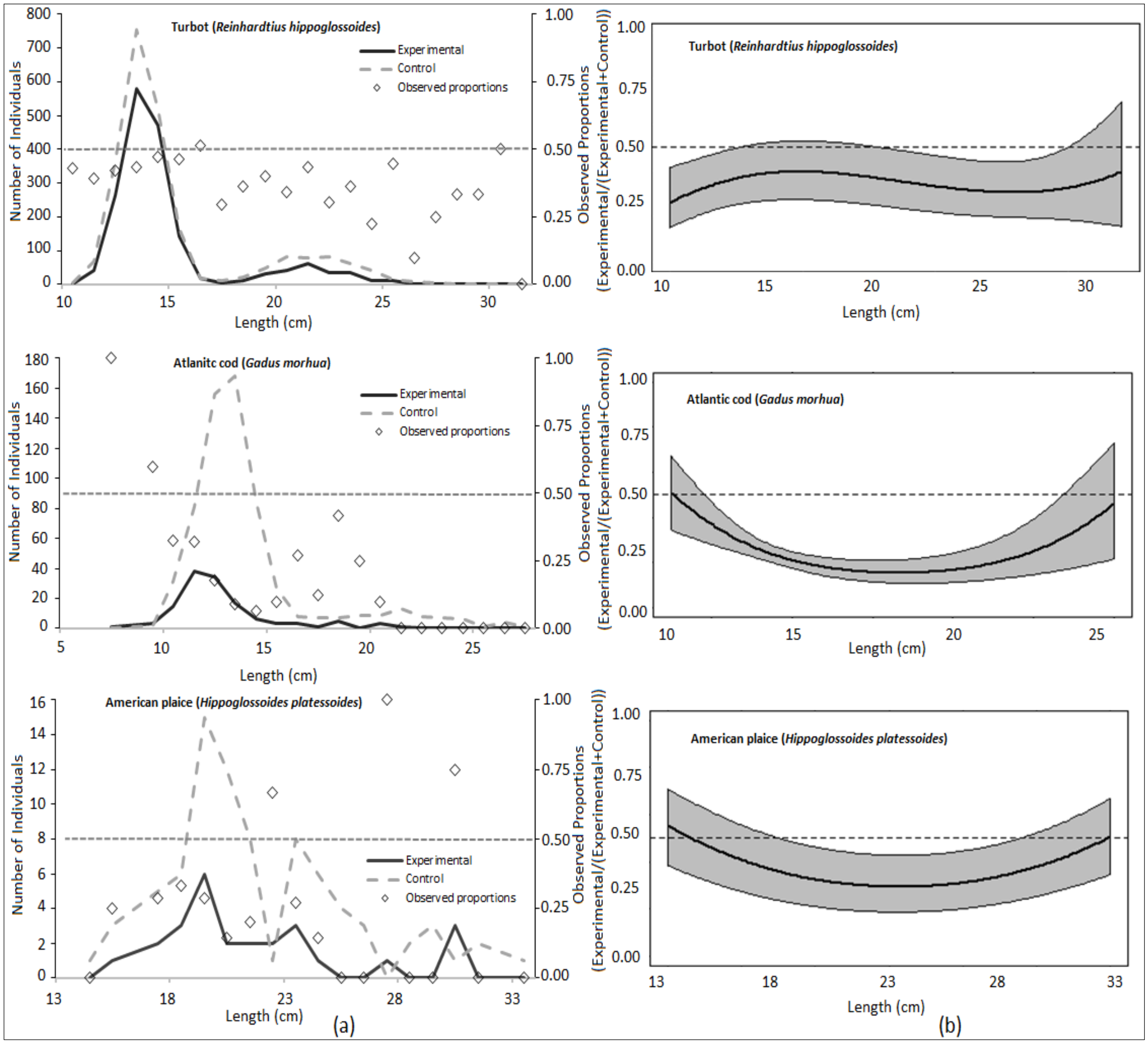

Figure 5.6: Experiment 2 – Pooled length frequency and observed proportions (experimental / (experimental + control)) of the total catches caught in the experimental 5-drop chain footgear trawl (a). Generalized linear mixed model (GLMM) modelled proportion of the total catches caught in the experimental 5-drop chain footgear trawl. Interpretation: a value of 0.5 indicates an even split between the two trawls, whereas a value of 0.25 indicates that 25% of the total fish at that length were caught in the drop chain footgear trawl and 75% were caught in the traditional rockhopper footgear trawl. The shaded areas around the mean curves (bold lines) are the 95% confidence regions (b).

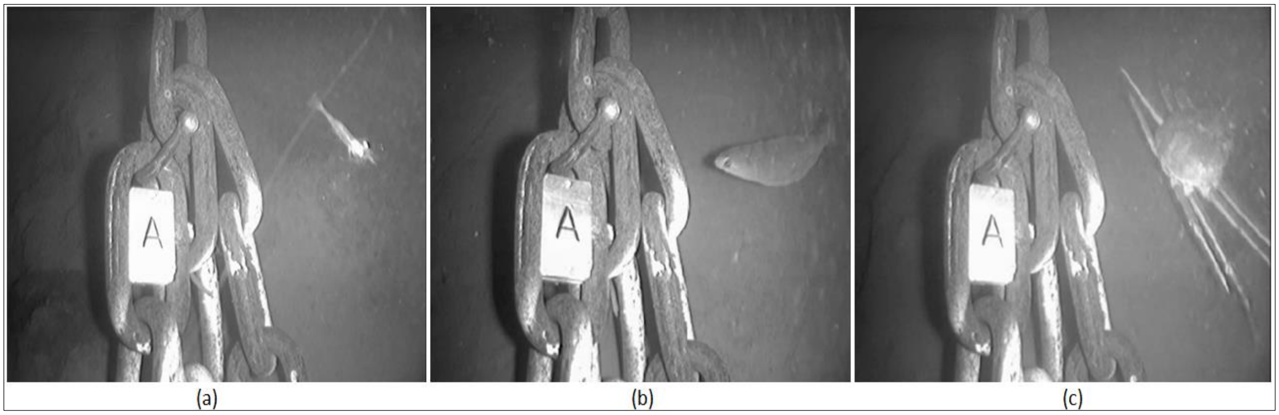

Figure 5.7: Images from an underwater video camera attached to the fishing line of the experimental-9 drop chain footgear trawl. Images show shrimp (a), turbot (b), and snow crab (c) in response to the approaching drop chain footgear.

Appendices

Video 5.1: Video demonstrating snow crab and bycatch in response to the approaching experimental 9-drop chain footgear. This is an engineering clip which was glued together (not a raw video). (To view video, see open access paper online at www.thejot.net (V10N2)

Table A5.1: Statistical summary of power analysis for shrimp catch in Experiment 1 (9-drop chain footgear vs. rockhopper footgear).

t tests - Means: Difference between two dependent means (matched pairs)			
Analysis:	Post hoc: Compute achieved power		
Input:	Tail(s)	=	Two
	Effect size dz	=	0.4554976
	α err prob	=	0.05
	Total sample size	=	10
Output:	Noncentrality parameter δ	=	1.4404099
	Critical t	=	2.2621572
	Df	=	9
	Power (1-β err prob)	=	**0.2518603**
t tests - Means: Difference between two dependent means (matched pairs)			
Analysis:	A priori: Compute required sample size		
Input:	Tail(s)	=	Two
	Effect size dz	=	0.4554976
	α err prob	=	0.05
	Power (1-β err prob)	=	0.95
Output:	Noncentrality parameter δ	=	3.6723391
	Critical t	=	1.9977297
	Df	=	64
	Total sample size	**=**	**65**
	Actual power	=	0.9512130

Chapter 6. Summary and Conclusions

This thesis addressed different key research aspects regarding the subject of development of what may be considered more seabed friendly bottom trawls. First, I investigated the behavioural interactions of individual snow crabs in response to the rockhopper footgear of a traditional inshore shrimp trawl used in Newfoundland and Labrador, Canada (Chapter 2). Second, I conducted an overview of three widely used trawl simulation software packages (i.e., DynamiT, SimuTrawl, and Trawl Vision PRO) and evaluated their design, simulation, and predictive capabilities (Chapter 3). I then examined how well computer simulation and flume tank testing of scale engineering models actually predict full-scale at-sea performance of bottom trawls (Chapter 4). Finally, I investigated the effectiveness of a novel footgear for reducing the seabed impacts of shrimp trawls off the east coast of Newfoundland and Labrador, Canada (Chapter 5). The following sections provide an integration of the major aspects of the results from these four research-based chapters. I also discuss limitations of the approaches used and future research directions.

6.1 Environmental Concerns Associated with the Northern Shrimp Trawling in Newfoundland and Labrador, Canada

The Newfoundland and Labrador’s northern shrimp fishery makes a substantial contribution to the province’s seafood industry and local economy with over 71 thousand tonnes harvested with a landed value of over $210 million dollars in 2014 (DFA, 2015).

Bottom trawling has been used exclusively as the only economically viable method to capture northern shrimp in the region. However, similar to many other bottom trawl fisheries around the world, the Newfoundland and Labrador shrimp fishery has been facing public pressure to amend its fishing practices to be more environmentally friendly and selective. Some sectors of the fishing industry in particular, have been raising concerns about the potential for unaccounted (unobserved) mortalities of snow crab which are exposed to shrimp trawling given the overlap in their fishing grounds (CCFI, 2013).

The findings from Chapter 2 demonstrate that snow crab were quickly overtaken under the footgear of the approaching trawl and a high number of the snow crab observed experienced an encounter with the rockhopper footgear components. I also found that the majority of the snow crab observed appeared to be aware of the trawl footgear and were actively responding and/or reacting to the approaching threat. However, I was unable to investigate the severity, degree of pain, or likelihood of mortality after passing under the footgear. In addition, my observations focused only on the centre of the footgear thus limiting the ability to evaluate interactions in other regions of the trawl. Given high number of encounters of snow crab with the rockhopper footgear, I qualitatively speculate that shrimp trawling should injure and/or damage snow crab, causing unobserved mortalities of snow crab. Past investigations are both consistent and inconsistent with this conclusion. An initial joint study between industry and both levels of government found no impacts of trawling on the snow crab resource (FDP, 2002). Gilkinson et al. (2006) similarly found no evidence that shrimp trawling imposes a substantial level of damage or mortality to snow crab in a study encompassing a broad depth range of 93-428 m and the entire range of bottom types encountered in the northern shrimp fishery. More recently, in the most comprehensive study on the issue, Dawe et al. (2007) concluded that shrimp trawling is not a major source of snow crab mortality but did conclude that there is a low incidence of leg loss (i.e., 10%) for crabs exposed to trawling at intensities higher than those that occur in the Newfoundland shrimp fishery. They found no significant increase in new leg loss in hard-shelled male crabs as a result of encountering the main footgear but reported significantly higher new leg loss (up to 30%) after repeated trawling (i.e., 6 times). Sightings of dead snow crab lying in the path of a bottom trawl have also been observed in some Newfoundland studies (Schwinghamer et al., 1998) but not others (Dawe et al., 2007). Other studies conducted by American scientists supported that there is a low incidence of damage to crabs caused by bottom trawls or the effects were varied by species for different gear components. For instance, Rose (1999) carried out an experiment with secondary trawls on Alaskan red king crab (*Paralithodes camtschaticus*) and found that only 5-10 % of crabs experienced damage of any kind resulting from contact with various trawl footgear types, including rockhopper gear. In a more recent study, Rose et al. (2013) studied crab mortalities after their escapes under the different components of a commercial groundfish trawl by using small recapture nets attached behind the sweeps, wings and central footgear. The authors concluded that immediate and delayed mortality rates of crabs varied significantly by species for the different trawl components they encountered, with red king crab (*P.*

camtschaticus) being more vulnerable than snow crab (*C. opilio*) or southern Tanner crab (*C. bairdi*).

So a new synthesis of the findings would strongly suggest that yes, bottom trawling off the coast of Newfoundland and Labrador (in every likelihood) kills snow crab, and we now have underwater video to document potentially damaging encounters what can lead to immediate long-term mortality. But the extent of mortality on a population remains uncertain. Some contend it is not a major source of mortality and there is no evidence to suggest ecosystem function is negatively altered as a result of trawling activity. Others contend any harm is to too much harm in the context of a precautionary approach.

Given the controversial nature of the issue, it is arguably only scientific studies that can provide facts regarding the situation. Personal livelihoods are on the line and emotions can be over-heated and deeply personal. It is into this situation, that we must show leadership and inject additional research and development in support of scientific knowledge. Further research should be conducted to better understand the interactions between snow crab and bottom trawling in Newfoundland and Labrador. See Section 6.5 for a list of recommended future research needs.

6.2 Research and Development of Fishing Gears

The development of fishing gears for the commercial fishing industry has improved dramatically over the last few decades. Concerns over ecosystem impact, bycatch restrictions, increasing regulations, and fuel costs are the major reasons for much of the improvements in fishing gear research and development occurring worldwide. The major advancements in computer simulation, physical modeling methods, and gear monitoring/controlling systems (e.g., underwater cameras, acoustics, and trawl-mounted sensors) have made fishing gears more sophisticated, enabling the fishing industry to harvest more efficiently and selectively, and in turn reduce ecological impacts in many fisheries.

The findings from Chapters 3 and 4 demonstrate the advantages and disadvantages of using numerical modeling and simulation, testing physical models in a flume tank, and conducting at-sea experiments of full-scale prototypes. The strengths and limitations of different commercially available trawl simulation software in terms of design capability, simulation capability, and reliability of results, were investigated and interpreted (Chapter 3). The study represent a unique and novel piece of work which has never been done before. Rather noteworthy, the study provides valuable knowledge and reference for stakeholders (e.g., gear designers, researchers, and educators) who are seeking advice about the features and accuracy of simulation software and who are considering using software for numerical modeling and simulation of fishing gears. The findings are believed to be greatly beneficial for the software developers to improve their products. This knowledge would also be a useful contribution to the fisheries research literature as numerical modeling is becoming one of the popular methods of evaluating trawl designs and assessing their performance during the early stages of gear development. In addition, I addressed the question of how well computer simulation and flume tank testing of scale engineering models actually predict full-scale at-sea performance of bottom trawls (Chapter 4). The results demonstrated that the complementary use of two or three methods should be encouraged for assisting the gear development cycle given their own weakness and merits. Moreover, I clarified that the precision and accuracy of the predictions depends on many factors. Thus, thoroughness and care must be emphasized in order to reduce bias in predicted performance.

The methods by which a new fishing gear (e.g., bottom trawls) is designed and tested will continue to be improved. Specifically, I predict that advanced mathematical modeling used in numerical simulation methods will be developed and applied in order to improve the current computational simulation capability, in particular the capability of predicting physical impacts associated to different bottom contact gear components (e.g., trawl doors, footgear/groundgear). Model scaling, construction, and evaluation of physical models in flume tanks will also continue to be improved and updated (i.e., improving flume tank testing capability with precision). In particular, increasingly modern instrumentation (e.g., optical, acoustical, and laser-scanning technology) will be used to evaluate (with greater precision) the performance of fishing gear in flume tanks (e.g., characterizing the location and downward forces of trawl components relative to the seabed). On the other hand, underwater applications (e.g., underwater cameras, acoustics, and trawl-mounted sensors, as well as active trawl/auto-trawl systems or “smart trawling technology”) for direct observation is expected to improve the evaluation of gear performance at sea, in particular the use of these advanced technologies to investigate potential impacts of bottom trawling on benthic communities and marine habitats.

Finally, I hypothesize that the use of computer simulation and testing of physical models in flume tanks or in tow tanks/wind tunnels will become, not only wise and prudent, but also the *de facto* standard before proceeding to full-scale comparative fishing experiments at sea.

6.3 Reducing Environmental Impacts of Northern Shrimp Trawling in Newfoundland and Labrador, Canada

This thesis recognizes that bottom trawling can be brilliant in its engineering, and at the same time, detrimental to marine benthic communities and habitats if conducted in an unsustainable manner. Finding the right balance of sustainable harvesting practices is a global challenge in every fishery. While the potential impact of bottom trawling activities on habitats and benthic communities is not easy to predict and characterize for various reasons, I do believe that development and application of selective fishing techniques that are more environmental friendly, selective, and efficient, would be advisable.

The findings from Chapter 5 demonstrated seabed impacts of shrimp trawling in Newfoundland and Labrador can be reduced if the trawl footgear is made lighter and/or designed to have less contact with the seafloor. In particular, it was revealed that we are able to minimize the interaction or encounter of snow crab with the experimental drop chain footgear. As a result, I hypothesize that the likelihood of snow crab mortality in relation with drop chains is expected to be low or minimized. The advantage of this innovative footgear is believed to be beneficial for the sustainable development of the snow crab fishery which is the province's highest value fishery and one of Canada's most valuable fisheries with Marine Stewardship Council (MSC) certification. However, I admit that the results were only derived from a low number of paired tow comparisons and our video observations focused only on the centre of the footgear in which one drop chain was in the field of view. These limitations of the study have reduced my confidence of the catch rate comparison as well as the ability to evaluate interactions of snow crab with the drop chain footgear. I therefore recommend that additional work is needed to further improve the performance of drop chain footgear for the Newfoundland and Labrador's shrimp fishery.

Encouraging the introduction of more environmentally friendly bottom trawls into the fishing fleet is essential not only for the sustainability of the northern shrimp fishery, but also for the sustainability of the snow crab fishery (i.e., reduced potential unaccounted mortalities of snow crab which are exposed to shrimp trawling) in the Newfoundland and Labrador region. Bottom trawling is one of the most important components of the Canadian fishing industry (especially in the Atlantic region), representing approximately 35% of the total commercial catch in 2008 (DFO, 2011). A complete ban on existing mobile bottom trawl fisheries would lead to a loss of millions of dollars to Atlantic Canada's fishing industry as well as displacement of thousands of fishermen and plant workers.

6.4 Limitations of My Approaches

Several major limitations were identified during this thesis. The following section discusses them so as to inform the reader.

There have been considerable efforts in recent years to scientifically understand both direct and indirect effects of bottom trawling on decapod crab species (see Donaldson, 1990; Schwinghamer et al., 1998; Rose 1995, 1999; Gilkinson et al., 2006; Dawe et al., 2007; Rose et al., 2013). Underwater observations of the behaviour of snow crab encountering a shrimp trawl (Chapter 2) is a novel piece of research and to my knowledge it has never been done before. However, the experiments were not designed to investigate the severity, degree of pain, or likelihood of mortality of the crab either immediately or after passing under the footgear. This was a major limitation of my experiment. Another limitation was that my ability to detect individual crab (or for substrate types) relative to the rockhopper footgear components was limited by murky water and low light penetration, even when the camera system was attached to the fishing line to observe very close to the seabed with an additional lighting unit attached on the headline. However, this limitation is known as one of the common technological challenges when conducting species-specific behavioural observations in dynamic underwater environments (Hemmings, 1973; Bublitz, 1996; Underwood et al., 2012). The final limitation relates to artificial light which is well known to modify animal behaviour as it alters the underwater light field (i.e., light level, colour, and contrast) (Glass and Wardle, 1989; Walsh and Hickey, 1993; Engås et al., 1998; Olla et al., 2000). I recognize this was a limitation of the experiments and that the white light used may have altered crab behaviour and biased the results. Future studies should include this consideration in the investigation, such as carrying out the experiment with infra-red lighting to evaluate effect of white light. Or perhaps alternative technology, such as the newly developed Aris Sonar (Sound Metrics Inc.), could be used. This “acoustic camera” does not require artificial light and works well in turbid water.

Regarding my comparative study of different simulation software (Chapter 3), one of the major limitations of my approach was the limited number of software packages I was able to consider and evaluate. This limitation may limit our knowledge about the global development and application of numerical modeling and simulation method for fishing gear design and evaluation. A second limitation of the approach is that some of my evaluations about capabilities of design and simulation of each software, could be viewed as subjective. However, given I am neither a developer nor a seller of the software, I do believe I am independent in my analysis. But could I be biased? Because I may have more experience using one particular software (i.e., DynamiT) over the others, I was concerned I might be biased in my evaluations. However, I have made my best effort to judge each software equally fair. The approach used was systematic in nature, with data presented in figures and tables. I should also mention the work was conducted with full transparency with the developers. They were contacted in advance of the study, during the study, and after the study. Each was forwarded an electronic copy of the manuscript for their comment and review. So none of this has been done behind closed doors. This gives me added assurance that what I have created is a true representation of the software and can be published with scientific integrity.

Finally, there were (of course) limitations relating to my development of an environmentally friendly bottom trawl (i.e., drop chain footgear) for the Newfoundland and Labrador northern shrimp fishery. One of the major limitations of my approach is that the experimental results were only based on a limited number of paired tow comparisons. This limitation was believed to render the statistical conclusions questionable, especially with regard to the findings of non-significant difference on the catch rates of northen shrimp and bycatch between the experimental and traditional trawls (drop chain vs. rockhopper). For this reason, the manuscript had to place increased emphasis on the effectiveness of the engineering, and less emphasis on the catchability of the trawls. This limitation is clearly described in the chapter's discussion section. Therefore, I suggest further experiments with more tow comparisons are needed to statistically detect differences in catch rates of shrimp and bycatch. Another limitation that our video observations of snow crab interactions with the drop chain were limited to the centre of the footgear with only a single drop chain in the field of view. This limitation reduced my ability to investigate the real drop chain perforamnce and its potential herding effects on shrimp and bycatch species, especially the interaction (i.e., nature of encounters) between snow crab and the drop chains. Collection of more underwater video for other trawl components would greatly benefit future evaluations of the experimental drop chain trawl in comparison to the traditional rockhopper footgear trawl.

6.5 Future Directions

Scientifically understanding and documenting the impacts of bottom trawls on the ocean environment as well as development and application of more environmentally friendly bottom trawls still remains a hot research agenda that requires further efforts to address outstanding issues. The following parts provide some key interests for future research initiatives in order to support sustainable development of the northern shrimp fishery, as well as the snow crab fishery in the Canadian Atlantic, in particular Newfoundland and Labrador.

I recommend the following list of future research needs toward the goal of better understanding whether shrimp trawling negatively affects the snow crab population and their habitats:

1) Develop a method to estimate trawl-induced damage and/or mortality (i.e., estimate the force of footgear components on snow crab *in situ* and further, simulate the effects of this force on snow crab in laboratory experiments).
2) Repeat the experiment in Chapter 2 to evaluate the effect of white light on snow crab behaviour. This would involve instrumentation capable of "seeing in the dark" – perhaps infra-red light which is not visible to crab, or high frequency sonar (e.g., Aris Sonar) which does not require artificial light whatsoever.
3) Conduct more video observations of snow crab behaviour in response to other gear components, including trawl doors, wires/bridles, and wing-sections.

4) Conduct more video observations of snow crab behaviour in response to trawl components on different sediment types and on snow crab of various shell conditions, or at higher snow crab densities.
5) Conduct more video observations of crab behaviour with different footgear designs (i.e., bobbins)
6) Increase basic biological knowledge about snow crab visual acuity and sensory systems toward the goal of better understanding reaction behaviour.

I recommend the following list of future research needs with regard to the application of numerical modeling and simulation methods for fishing gear design and evaluation:

1) Continue to review and evaluate additional simulation software from different developers/providers. This is necessary because in a competitive capitalist world, there is a constant updating of existing software and the release of new software products.
2) Compare the performance of different simulation software in their ability to simulate other trawl types/designs (e.g., commercial trawl designs, twin trawls, pelagic trawls, outrigger trawl systems).
3) Conduct comparisons of different simulation software for their abilities and capabilities to predict/estimate the seabed impacts of different gear components or for the purposes of reducing fuel consumption or gear resistance.

I recommend the following list of future research needs toward the goal of developing environmentally friendly shrimp trawls for Newfoundland and Labrador, in particular, the refinement of the drop chain trawl concept:

1) More comparative fishing experiments with larger sample size (i.e., more paired tows) are essential to clarify the effectiveness of the drop chain footgear trawl over the traditional rockhopper footgear trawl.
2) Collect more underwater video observations of drop chain footgear performance for other parts of the footgear (e.g., bunt and wing-sections) to understand its herding effects on shrimp and bycatch species, in particular the interaction/encounter of snow crab with the drop chains.
3) Further engineering is needed to determine how to minimize the snagging of chains caused during rolling on net drums as well as tear-ups while fishing. In addition, instrumentation for monitoring contact chains and the height of fishing line off the seabed would also be of benefit.
4) Other gear modifications (e.g., semi-pelagic trawling or off-bottom doors, floating bridles) should also be investigated for developing low-bottom impact shrimp trawls.

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