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Numerical Modeling - A Comparison of Different Methods for Simulating Bottom Trawls

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Abstract

Bottom trawls are fishing systems that are towed behind vessels for the purpose of catching fish and shellfish for commercial and scientific purposes. The dynamic behaviour of a bottom trawl is largely affected by its design, construction, rigging as well as the hydrodynamic and frictional forces experienced while towing along the seabed. Numerical modeling of bottom trawls is essential for understanding and predicting trawl geometry, resistance and downward forces on the seabed under different conditions. Currently, the market offers a number of trawl simulation software packages. Some have powerful features while others provide basic features for numerical modeling and simulation. In this study, we present an objective evaluation of three widely used trawl simulation software packages: DynamiT, SimuTrawl, and Trawl Vision PRO. A detailed overview of each trawl simulation software, as well as an evaluation of their design and simulation capabilities and reliabilities are discussed. This study provides valuable knowledge for fishing companies, trawl designers, net makers, researchers and educators who use numerical modeling methods for simulating bottom trawls.

Keywords: bottom trawl, simulation, DynamiT, simutrawl, trawl vision PRO

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 (Fiorentini et al., 2004; Lee et al., 2008; Queirolo et al., 2009 and Nguyen et al., 2015).

Studies on the dynamic behaviour and performance of mobile fishing gear systems (bottom trawls) have been investigated for several decades using various theoretical and experimental methods (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 (external forces such as drag force, shearing force, sinking force and buoyancy) and the properties of the materials used (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 & Marichal, 1998; Lee & Cha, 2002; Lee et al., 2005;

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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 (DynamiT, Trawl Vision PRO and SimuTrawl), 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 (Makarenko et al., 1998; Priour, 1999, 2013; Freiria, 2012; Lee et al., 2005, 2008; Vincent & 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 the 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 (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 (CadTrawl and CATS) for simulation of trawl performance (Hansen & 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 using numerical modeling method for simulating bottom trawls.

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

DynamiT is a comprehensive trawl simulation softwaredeveloped 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 & Roullot, 2006). This involves solving several equilibrium equations at the same time (equations of the dynamic mechanic balance, equations taking into account the elasticity of the bar, 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 are also 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 & 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 (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 Marlenet 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 DynamiT to predict the performance of physical models in a flume tank.

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 trawls, including mid-water trawls, bottom trawls, multi-rig trawls, pair trawls and Danishseines. 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 (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 & Cha, 2002; Lee et al., 2005). This model expresses the constituents of a virtual fishing gear system as mass points (the knots of its mesh are considered as mass points) having mass and mass-less springs (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 (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 & Lee (2000), Lee & Cha (2002) and Lee et al. (2005) described a physical modeling method (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 & Cha, 2002; 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). Most 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 PROis 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 design scan be viewed under various rigging, towing speed and depth scenarios (AcruxSoft, 2012a). In addition to the design and simulation programs (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 & Yamazaki (1975), Wileman & Hansen (1988) and Ferro & 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 TrawlVision, named AcruxSoft 2.0, was developed and initiated in 1989 by Frank Chalkling (Chalkling, F., Personal communication). 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).

Materials and Methods

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 & 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 rock hopper 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 (Fig. 1). The design has changed very little over time as a result of stringent standardization of construction and operational protocols (Walsh et al., 2009).

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

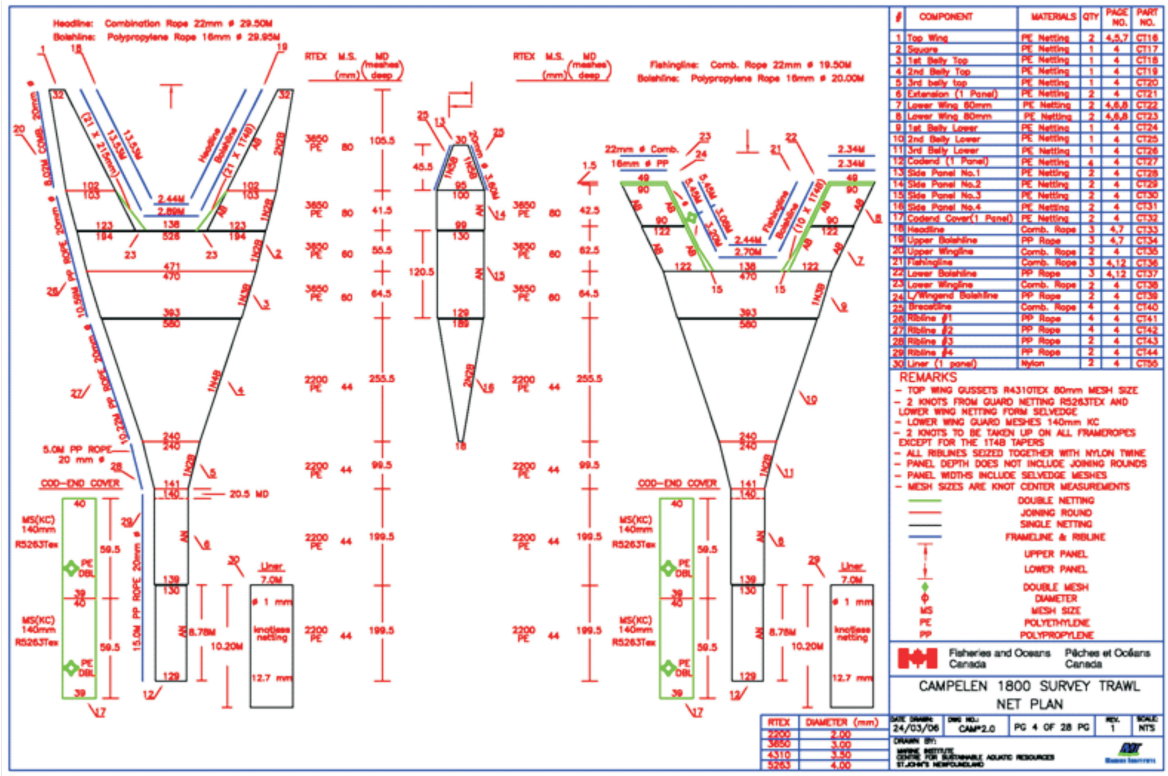

Fig. 1. Schematic netplan of the Campelen 1800 demersal survey trawl (Walsh et al., 2009)

The capability of each software package was evaluated using a number ofcriteria (Table 4). This included the ability of the software to describea variety of complex trawl designs (complicated riggings and multiple wingtips) and simulate these trawls under different fishing conditions (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 (abilityfor designing reusable user defined elements), modeling assistance (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).

Each of the three software packages was utilized to simulate the mechanical behaviour of the Campelen 1800 trawl (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 kn for 7 different towing depths (250, 500, 750, 1000, 1250, 1500 and 1600 m). 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 fortrawl geometry (door spread, wing end spread and headline height) and trawl resistance (warp tension) at a standardized speed of 3.0 kn (speed over ground) and seven depths (250, 500, 750, 1000, 1250, 1500 and 1600 m) (see Gardner, 2012; 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 (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.

Results and Discussion

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 (material, runnage, mesh size and shape, diameter, yarn stiffness and braiding factor)
- Strengthening ropes (material, diameter, stiffness and mass/apparent mass)
- Floatation and footrope/footgear (material, volume, mass, and buoyancy)
- Rigging information-any combination of cables can constitute the rigging such as warp/ sweeps/bridles (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 (mesh size and shape and knots). Information on material, runnage and stiffness are not requested;
- Strengthening ropes (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 (three different standard riggings are available).

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.

The process of designing and simulating a trawling system in DynamiT is described in Fig. 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. The Simulation Document is used to run, control a numerical simulation and to analyze its output results.

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 3A. Entering and defining all the trawl design components (entering all the netting panels and strengthening

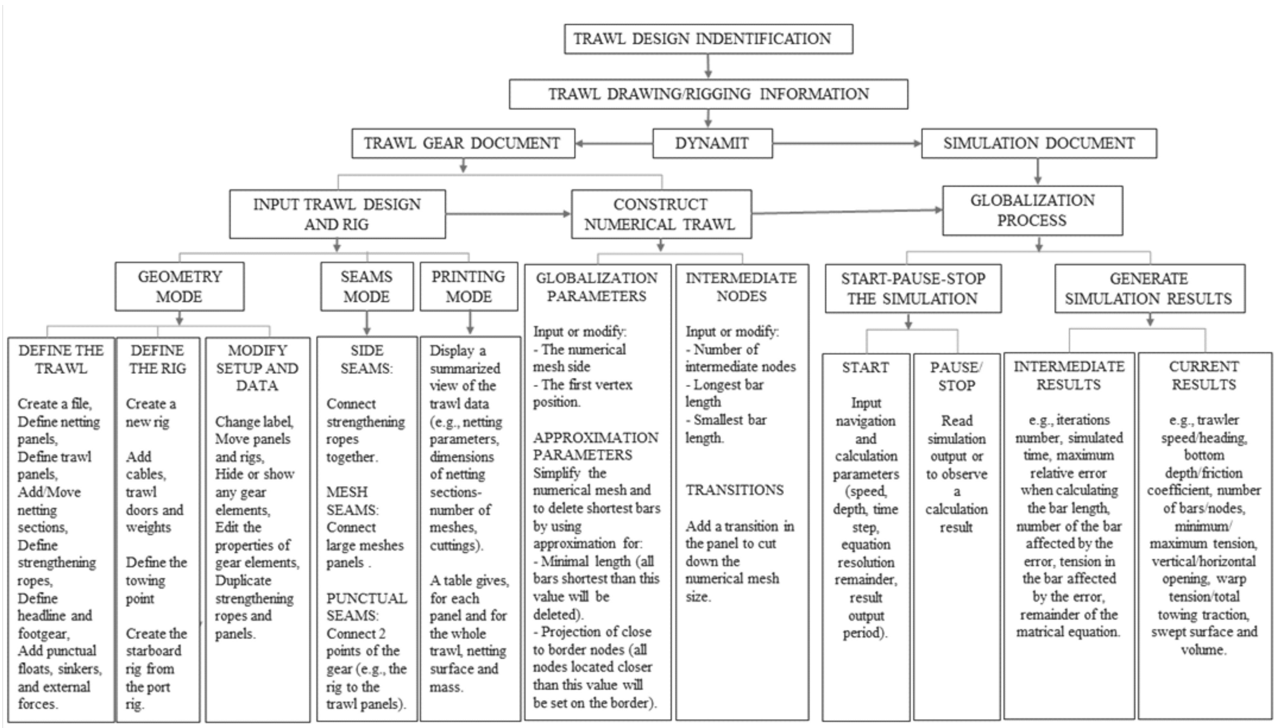

Fig. 2. Flowchart of the DynamiT design and simulation process.

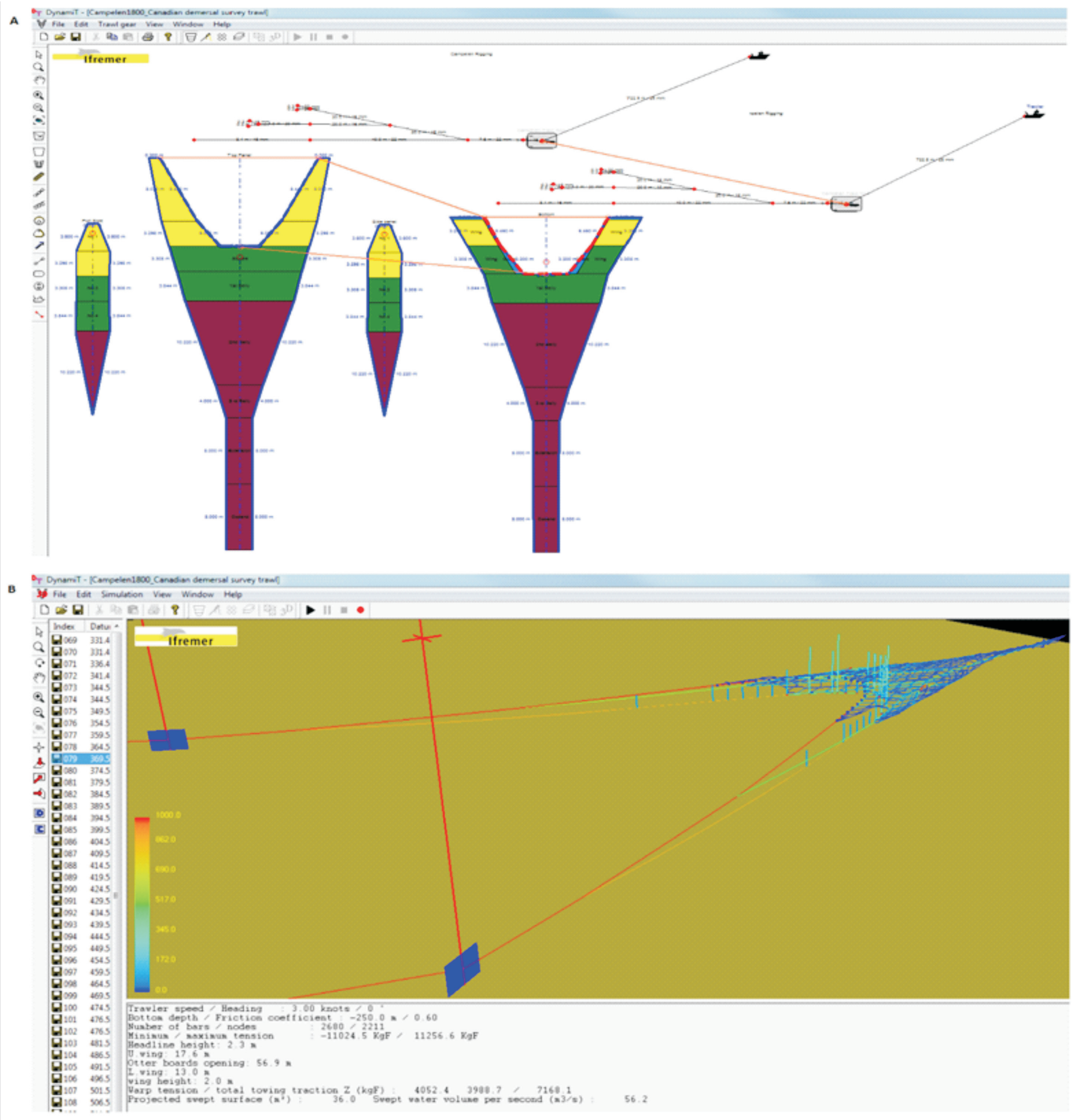

Fig. 3. Examples of the graphic interface in the DynamiT software for the Campelen 1800 trawl: (A)Trawl Design Mode-Trawl Gear Document. (B) Simulation Mode-Simulation Document.

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, and 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 (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 (Fig. 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 (door spread, wing spread, headline height and swept area) and forces (warp/bridle tensions and bottom contact forces produced by doors and footgear) across different towing speeds and depths (Fig. 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 (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 (Fig. 3B). DynamiT also allows the user to optimize the design process by changing input parameters during the simulation (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 (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 (desktop computers) and gear modeling scientific theory and knowledge. Numerical simulations are performed using certain assumptions regarding hydrodynamics (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 (any change of parameter is taken into account instantaneously, the sea is quiet/ no swell), doors (the angles of doors are constant relative to the flow direction, lift and drag coefficients are constant), seabed (no relief on the ground, no door spreading effect due to its digging effect in the substrate), footgear (the diameter of bobbins/ rubber discs are not taken into account) and catch (the catch is not simulated).

The process of designing and simulating a trawling system in SimuTrawl is described in Fig. 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 (trawler, trawl doors, and warp/sweeps/bridles) in another mode which is known as the Simulation Mode (Fig. 4 and 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)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 Fig. 4).

The Simulation Program of SimuTrawl is used for simulating and predicting the engineering performance of a trawl (Fig. 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 (distance between doors, wing-ends, headline and fishing line and swept area) and trawl resistance (tension on the warp, doors, bridles and net) (Fig. 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 (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 (Fig. 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 (behaviour of gear element is steady state is the time to finish the calculation). Whereas, the DynamiT is able to terminate (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.

The process of designing and simulating a trawling system in Trawl Vision PRO is described in Fig. 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 (Fig. 7A) in which the user can modify

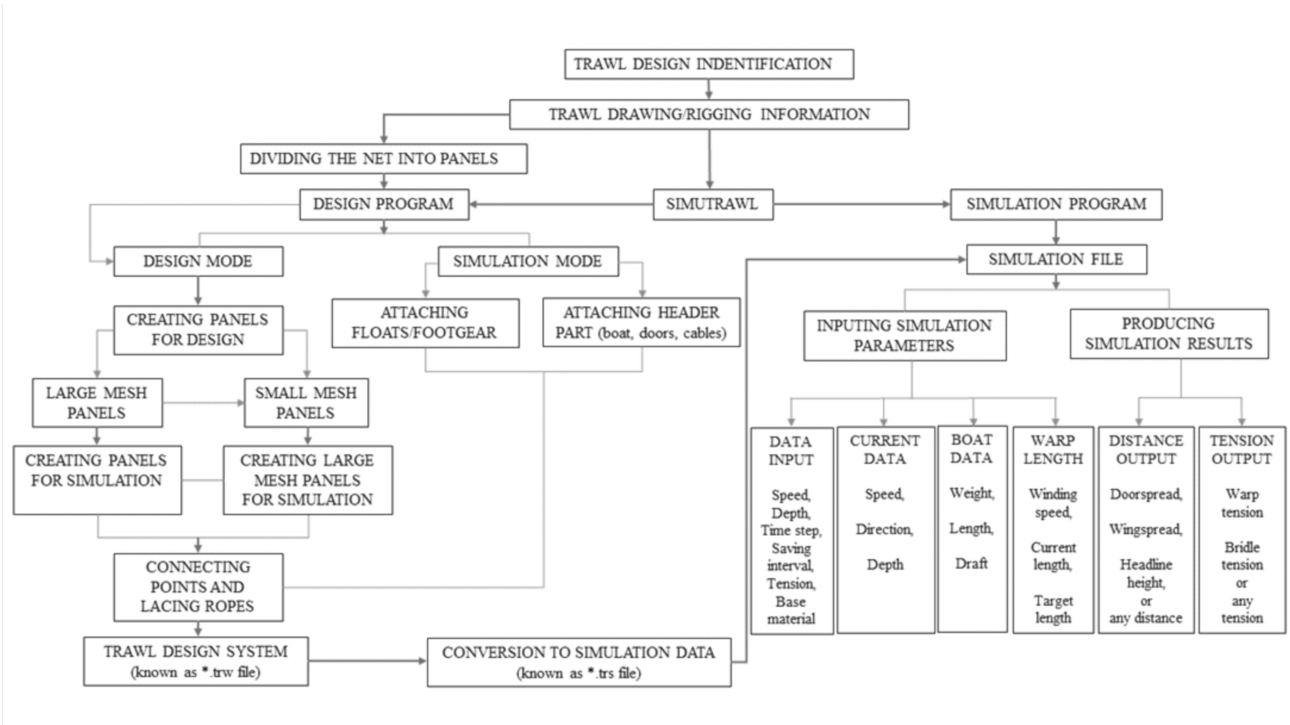

Fig. 4. Flowchart of the SimuTrawl design and simulation process.

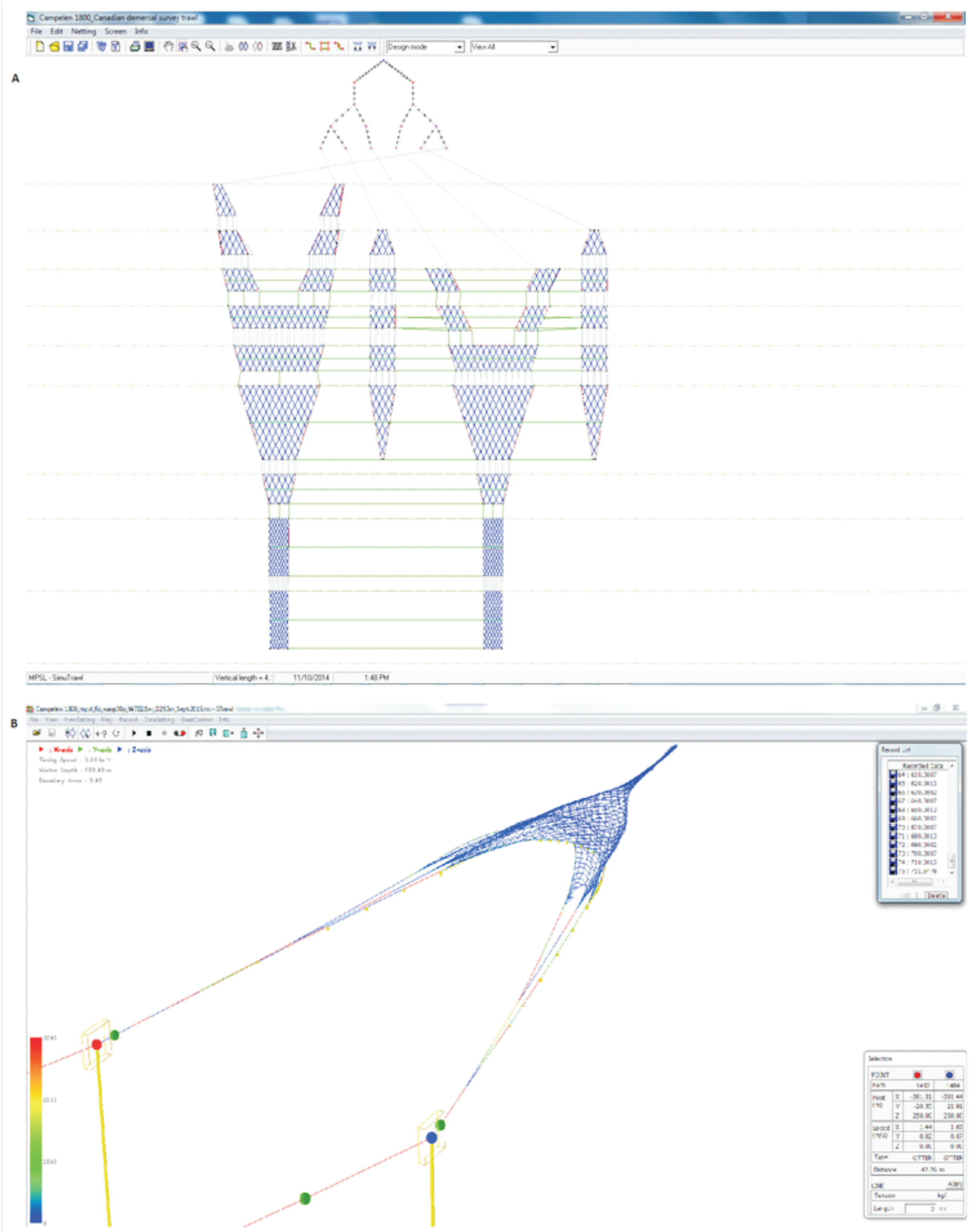

Fig. 5. Examples of the graphic interface in the SimuTrawl software forthe Campelen 1800 trawl:(A) Trawl Design Mode. (B) Simulation Mode

parameters for netting panels (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 (horizontal/vertical coefficients and angular coefficient) or rigging adjustment options (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, whereas this capability is developed in both DynamiT and SimuTrawl. Given the lack of parameter input by users (see section 3.1 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 (Fig. 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 (trawl doors) 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.

Comparison of the DynamiT simulations against at-sea observations are shown in Table 1 and Figure 8. 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

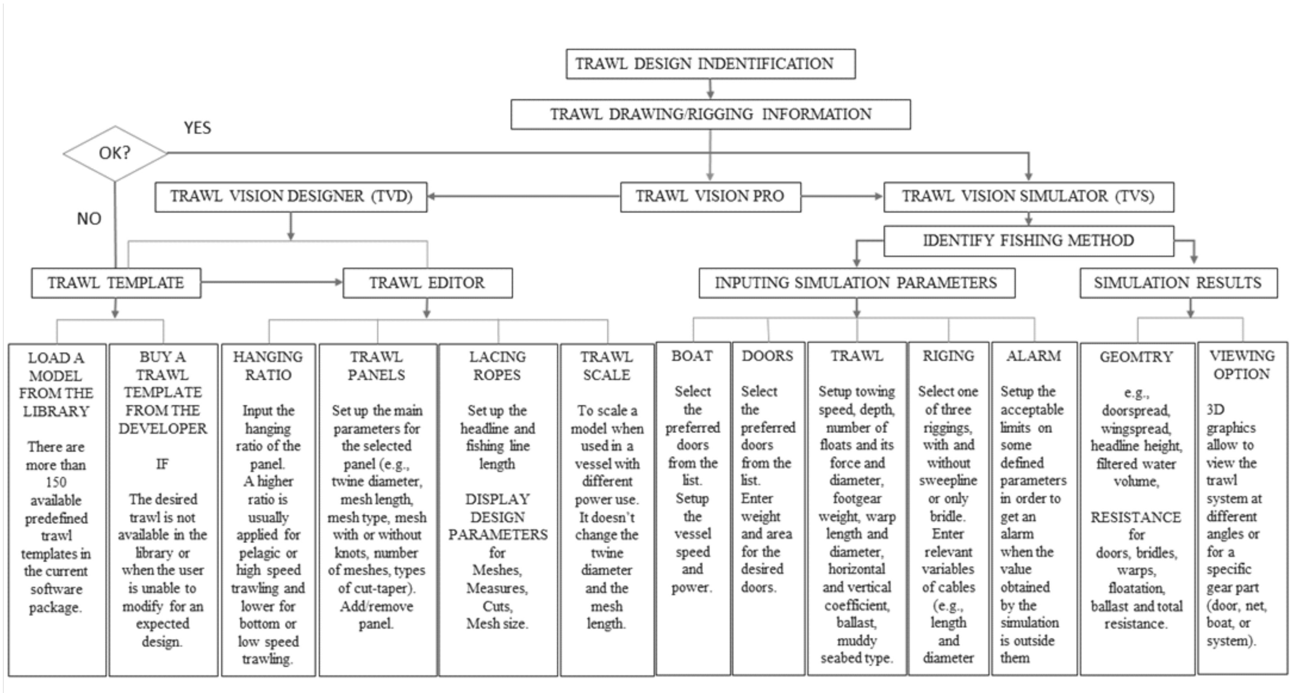

Fig. 6. Flowchart of the Trawl Vision PRO design and simulation process.

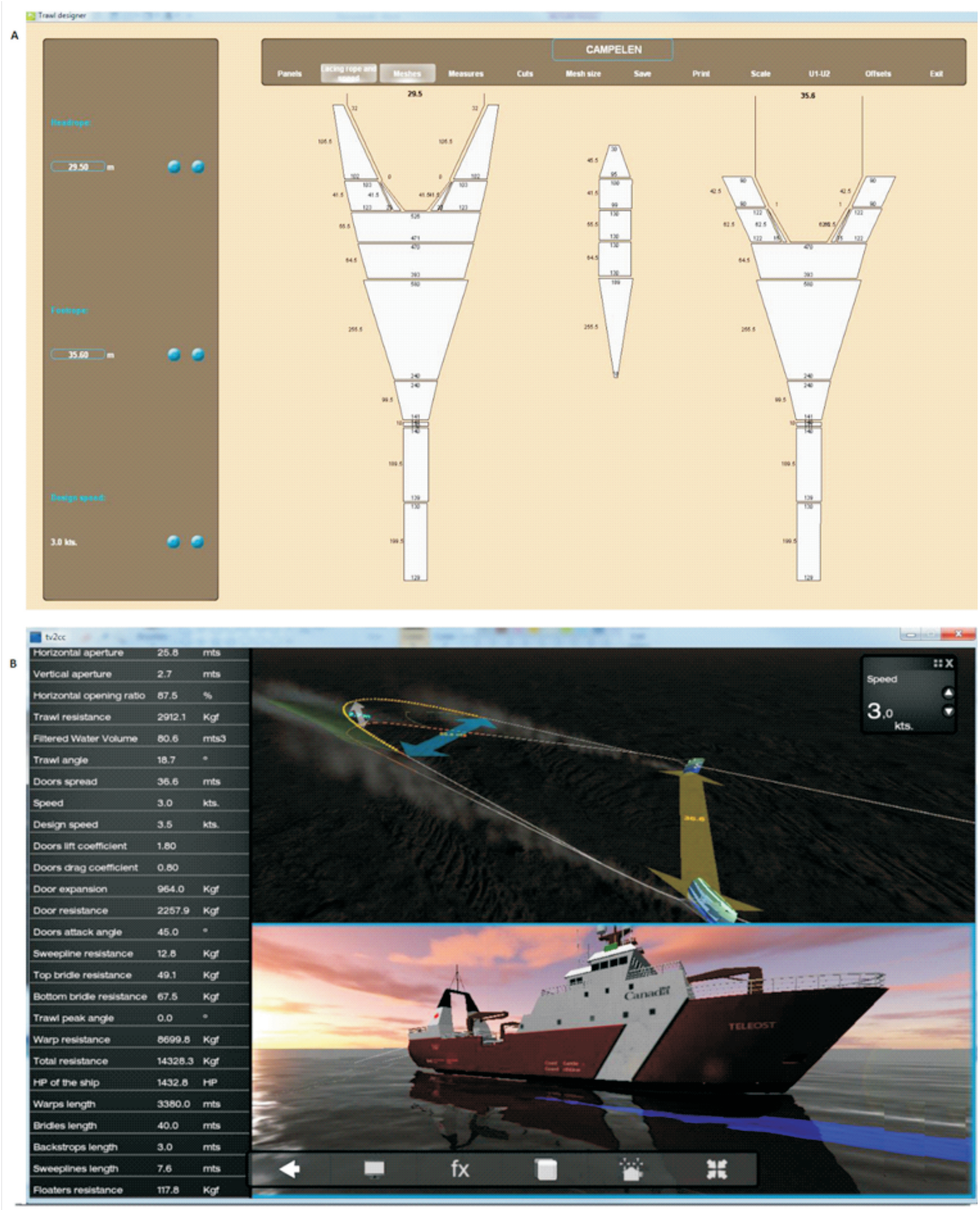

Fig. 7. Examples of the graphic interface in the Trawl Vision PRO softwarefor the Campelen1800 trawl: (A) Trawl design Mode/Trawl Editor Mode. (B) Simulation Mode.

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 Table 2 and Fig. 8. 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 Table 3 and Fig. 8. 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).

Table 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	250	53.9	55.9	17.9	17.6	2.9	2.3	10.5	7.2
Simulation	500	58.4	57.1	18.6	17.9	3.3	2.3	11.4	9.2
vs.	750	61.0	58.4	19.1	17.9	3.1	2.4	11.5	10.2
Full-scale at	1000	61.2	58.5	19.1	18.0	3.0	2.4	14.3	11.4
sea observations	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	

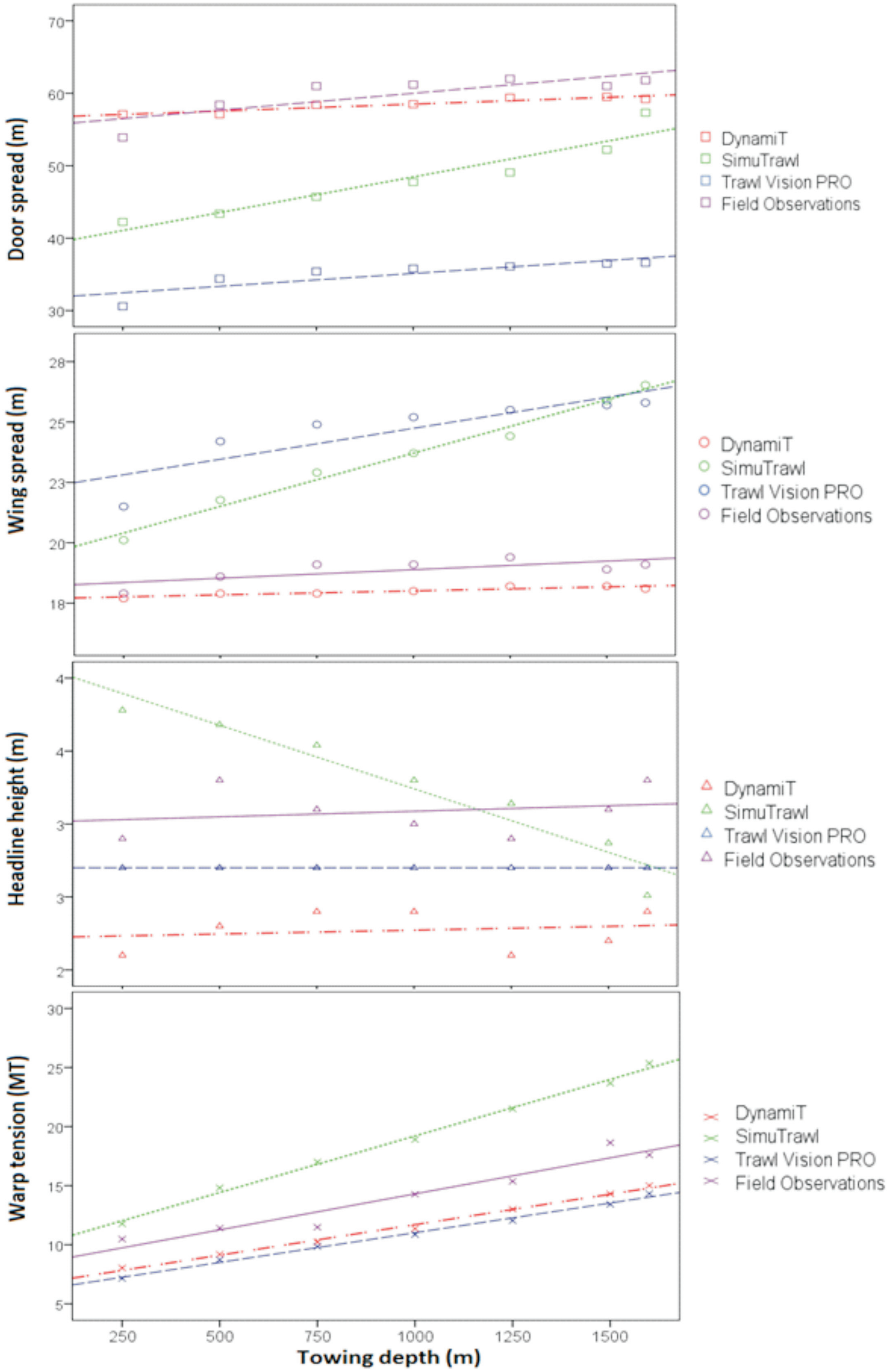

Fig. 8. The Campelen 1800 door spread, wing spread, headline height and warp tension in relation with towing depth at towing speed of 3 knots. The best fit regression lines are shown for each scatter plot.

Table 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	250	53.9	42.2	17.9	20.1	2.9	3.8	10.5	11.8
Simulation	500	58.4	43.4	18.6	21.8	3.3	3.7	11.4	14.8
vs.	750	61.0	45.7	19.1	22.9	3.1	3.5	11.5	17.0
Full-scale at	1000	61.2	47.8	19.1	23.7	3	3.3	14.3	18.9
sea observations	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. 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	250	53.9	30.6	17.9	21.5	2.9	2.7	10.5	7.2
PRO Simulation	500	58.4	34.4	18.6	24.2	3.3	2.7	11.4	8.7
vs.	750	61.0	35.4	19.1	24.9	3.1	2.7	11.5	9.9
Full-scale at	1000	61.2	35.8	19.1	25.2	3	2.7	14.3	10.9
sea observations	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	

This study provides useful knowledge regarding the strengths and limitations, capabilities and reliabilities for three commercially available trawl simulation software packages. We 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, we feel this evaluation was unbiased and objective. Every effort was made to learn and apply each software equally well. Table 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, we 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 amongst 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 (the trawl does not perturb the water velocity). Moreover, the footgear height is not simulated with a high degree of fidelity (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 (current, wind and swell) (Fiorentini et al., 2004; 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 (Zachariassen, K., Personal communication; Olsen,J., Personal communication) 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 Simu Trawl, 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 the secreate bias in predicted values compared to the real world performance. For example, SimuTrawl predicted a higher (25.4%) warp tension (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 (Lee, C. Personal communication), 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

Table 4. A summary of the evaluations and impressions of each software.

Specifications	Characteristics	DynamiT	SimuTrawl	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, Windows XP
	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 Danish
	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 centers	Research institutes, fishing schools, training centers (for teaching and training), fishing companies
	Main purpose	Research oriented	Research oriented	Education/training oriented
	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 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.	Study trawl geometry and forces of new or existing trawl gears, how a trawl can be modified to reduce the fuel consumption.
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 support	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 commands	Provided	Provided	Not Provided

Design capabilities	Templates requirement	No	No	Yes
	Input requirement	Intensive Input Data	Intensive Input Data	Less Input Data
	Number of elements in the model	Large	Large	Small
	Current control	Possible	Possible	Not Possible
	Ground friction/ seabed type control	Possible	Not Possible	Possible (only for muddy seabed)
	Complex gear system design application	Possible	Possible	Not Possible
	Data reusability	Possible	Possible	Possible (only trawl doors/trawl design templates)
	Database available	Not Available	Available	Available
	Ease of entering input	Easy	Moderate	Very easy
	Numerical gear generation/assumption	Applicable	Applicable	Not Applicable
	Writing comments/ notes in model building activity	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 of the model	Provided	Provided	Provided
	Playback	Provided	Provided	Not Provided
	Zoom function	Provided	Provided	Provided
	Multiple screen layout	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
	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

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 (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 (Rodriguez, F., Personal communication).

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 (door spread, wing spread, and headline height) as well as hydrodynamic forces acting on the trawling system (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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