

Optimization of Tidal Windows for Deep-Drafted Vessels by Means of *ProToel*

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Abstract—The access policy to ports for deep-drafted ships making use of channels which are subject to waves, tides, currents, wind and other complicating factors can be based on either deterministic or probabilistic principles. *ProToel* is a calculation tool for determining tidal windows for marginal vessels arriving at or departing from ports located at the Belgian coast or in the Scheldt estuary. The paper provides an overview of possible criteria to be fulfilled for a vessel to have access to approach channels. The outlines of the software are described and applications for short-term decisions and long-term accessibility studies are discussed.

Keywords—tidal windows; probabilistic access policy

1. INTRODUCTION

The access policy to ports for deep-drafted ships making use of channels which are subject to waves, tide, currents, wind and other complicating factors can be based on either deterministic or probabilistic principles. On one hand, a deterministic policy is based on minimum values for specific criteria, such as the gross under keel clearance (expressed as a percentage of the ship's draft), magnitude of (transverse) current components, degree of penetration into fluid mud layers. On the other hand, in a probabilistic approach the strict values for some of the criteria are replaced by an acceptable value for the probability of undesired events, such as the probability of touching the bottom during a transit. The selection of a probability based criterion for bottom touch requires the introduction of a minimum manoeuvring margin as an additional criterion.

ProToel is a calculation tool that has been developed by the Maritime Technology Division of Ghent University and Flanders Hydraulics Research (Antwerp) on behalf of the Flemish Government for determining tidal windows for deep-drafted ships approaching and leaving the Flemish coastal harbour of Zeebrugge and the Western Scheldt estuary. Recently an extension has been performed for the harbours located upstream the river Scheldt (Sloehaven, Terneuzen, Antwerp). The software allows to implement both deterministic and probabilistic criteria, so that a comparison can be made between different decision policies.

As input, the calculations need hydro-meteo data (directional wave spectra, tidal levels, currents) as a function of time in a number of reference points along the trajectory, bottom levels, ship characteristics and the ship's speed pattern. The calculations are performed for a number of possible departure times with a time interval of 10-15 minutes so that a tidal window can be obtained. Use is made of a database containing response functions for the vertical motions in waves and squat data for a selection of representative ships. The database contains both results of model tests carried out in the Towing tank for manoeuvres in

shallow water (co-operation Flanders Hydraulics Research & Ghent University), as well as calculated values. The hydro-meteo data can be either forecasted values or measured historical data; in case of forecasts, an uncertainty on e.g. the predicted significant wave height can be accounted for. Also on the bottom level a standard deviation can be introduced, so that local variations of the bottom depth can be dealt with. Implementation of other effects that may affect the vertical motions of the ship and, hence, the probability of bottom touch, such as wind and bends, is in progress.

In the following chapter, criteria commonly applied in access channels, either in a deterministic or probabilistic framework, will be discussed. Chapter 3 will provide an overview of the ProToel software, while examples of practical applications will be given in Chapter 4.

2. CHANNEL ACCESS CRITERIA

A. *Criteria Related to Vertical Clearances*

During the transit of the ship through the access channel, a comparison between the vertical dimensions of the vessel and of the waterway should result into acceptable margins. In principle, both the characteristics above and under the waterline may be of importance. In case of free height limitations, e.g. due to the presence of bridges, power lines or other overhead structures spanning the waterline, the air draft clearance should be sufficient to avoid contact with the ship's superstructure. Below the waterline, a suitable vertical distance should be maintained between the ship's keel and the channel bottom, for different reasons:

- to avoid contact between keel and bottom;
- to guarantee the ship's controllability and manoeuvrability.

The vertical distance between the ship's keel and the bottom depends on a number of factors that may be related to the ship, the water level and the bottom.

Ship related factors include:

- the ship's draft (aft and fore) in still water conditions, which may be variable due to density variations over the ship's passage through the channel;
- the vertical motion of the ship due to squat, which depends on the ship's speed through the water, the ship's geometry and the water depth;
- wave induced vertical ship motions (heave, pitch, roll);
- wind induced heel;
- heel due to centrifugal forces in bends.

In maritime access channels connecting a port with full sea, factors related to the water level are mainly caused by tidal effects. Tides are principally driven by astronomic phenomena, but meteorological effects (mainly wind) may cause deviations.

Finally, bottom related factors are linked with the dredging execution tolerance, and with allowances for bottom changes between maintenance dredging cycles and for uncertainties of bathymetric survey data. Additional requirement may be formulated in case the channel bottom is covered with a fluid, low-density mud layer.

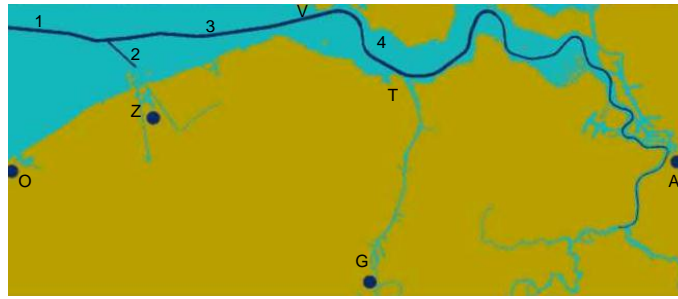


Fig. 1. Access channels and harbours in the Scheldt estuary: 1: Scheur West, 2: Pas van het Zand, 3: Scheur East, 4: Western Scheldt. A: Antwerp/Antwerpen (B), G: Ghent/Gent (B), O: Ostend /Oostende (B), T: Terneuzen (NL), V: Flushing/Vlissingen (NL), Z: Zeebrugge ((Eloot et al., 2009; www.maritiemetoegang.be).

Under keel clearance (UKC) related channel access criteria can be formulated in a deterministic or a probabilistic way, or in a combination of both. Deterministic criteria mostly prescribe a minimum value for the gross under keel clearance (i.e. the difference between the bottom depth and the static draft), expressed either in metre or as a percentage of the ship's draft. This value depends on the channel, taking account of the local wave climate and the ships' speed range. In the channels giving access to the ports located at the Flemish coast and along the river Scheldt, the following values are currently applied (Fig. 1): 15.0% (20%) of draft for *Scheur West* and *Scheur East*, 12.5% (20%) of draft for *Pas van het Zand* and the Dutch part of the *Western Scheldt*, 10.0% of draft for the Scheldt river on Belgian territory, 10% (15%) for the Zeebrugge outer harbour area (i.e. within the breakwaters) and 1.0 m for the Sea Canal from Terneuzen to Ghent. The values between brackets are applicable to LNG carriers. An additional operational condition is applied in the Zeebrugge area with respect to the vertical penetration of the upper fluid mud layer, for which a maximum value of 7% of the ship's draft is considered to be acceptable.

Probabilistic approach policies, on the other hand, are based on an acceptable probability of bottom-ship contact during the passage of one single ship. Such an acceptable probability of bottom touch is related to the consequences of such a contact – as after all it is the risk (probability * consequence) which has to be kept under control – and an accepted return period for such an undesired event, so that the intensity of the shipping traffic making use of the channel is of importance as well. Acceptable return periods are proposed in the Spanish recommendations for design of maritime works (Puertos del Estado, 1999); depending on the channel bed conditions (hard, medium, soft), the type of channel (general navigation channel or specific industrial channel) and the level of risk of loss of human life or environmental damages in the event of an accident, typical return periods vary between 15 and 800 years. For example, an acceptable return period of 25 years is proposed for events with low risk of loss of human life or environmental damages in a general navigation channel (i.e. a channel not in service of an industrial facility or a single specific terminal) with a soft bottom. Combined with the annual number of deep-drafted vessels making use of the channel, an acceptable value for the probability of bottom touch per transit can be derived; typical values are in the order of magnitude of 10^{-4} . However, a probability of bottom touch criterion needs to be accompanied by an additional condition to guarantee the manoeuvrability and controllability of the vessel, as these properties deteriorate significantly with decreasing under keel clearance. Such a criterion can be formulated in terms of either a minimum gross under keel clearance or a minimum manoeuvrability margin, the latter being defined as the time-averaged clearance under the ship, incorporating the effects of water depth, draft, squat and (wind and bends induced) heel, but excluding the oscillatory effects caused by wave action. The manoeuvrability margin criterion will overrule the probability of bottom touch criterion in areas protected from wave impact and in case of favourable weather conditions. PIANC Working Group MarCom49, "Horizontal and vertical dimensions of fairways" (report in review), suggests a minimum manoeuvrability margin of 5% of draft or 0.6 m, whichever is greater.

B. Criteria Related to Horizontal Disturbances

Safe transit may also be jeopardized by horizontal disturbances, such as wind and current. Sometimes maximum values for wind strength are accepted for arrival and departure, depending on the ship type and dimensions and often coupled to required tug assistance. Typical periods for generalized wind forecasts with acceptable accuracy are in the order of magnitude of 48 hours (PIANC, 2012); therefore, a wind criterion will have an effect on a different time scale compared to effects caused by tidal action.

For currents, on the other hand, at least if they are of tidal origin, long-term forecasts can be issued, so that they can be used in the frame of a deterministic or probabilistic approach policy, if applicable. Criteria concerning current may be linked to a maximum value for the cross current; as an example, arrival and departure of LNG carriers to the Port of Zeebrugge is not allowed when the cross current at the breakwaters exceeds a value of 2 knots (departing small, conventional and Q-flex types; arriving small LNG vessels) or 1.5 knots (arriving conventional, Q-flex and Q-max vessels; departing Q-max vessels), (Gyssens, 2011). For other vessels, 2 knots is considered as a maximum value for arrival or departure.

Instead of a maximum value for the cross current velocity, a current window is often formulated as a time of arrival relative to the tidal cycle. For instance, a tidal window for bulk carriers with destination Antwerp (Berendrecht Lock) or Flushing (Sloehaven) are only accepted if it contains a specific point in time with respect to high water at a certain location (e.g. 70 minutes past High Water in Flushing, 60 minutes past High Water at Prosperpolder).

3. PROTOEL

A. Structure

The ProToel software, developed in an object oriented programming environment, making use of Java, allows a user to select a ship with a specific loading condition, a route to be followed with a specified speed profile along the trajectory, defined either over ground or through the water, and a specific starting point (of series of points) in time for the voyage. In each point of the trajectory, the program calculates the gross UKC based on bottom depth and water level data, the manoeuvrability margin taking into account the squat which is a function of the ship's speed through water, and the bottom touch probability due to the local and temporal wave conditions. The results are compared to the governing criteria. A detailed description of the algorithms is given by Vantorre et al. (2008).

ProToel requires the availability of a number of databases:

- a ship database with squat data and dynamic wave response characteristics for a large range of ship dimensions and types, valid for a realistic range of forward speeds, drafts and water depths;
- a database of trajectories and trajectory points, containing bottom data;
- hydro-meteorological data for a number of locations as a function of time: tidal elevation, current speed and direction, wave characteristics, water density, wind.

B. Input data

The selection of input parameters by the user (ship type and dimensions, loading condition, trajectory, speed profile, starting time(s) for the journey(s), origin of bottom and hydro-meteo data) can be performed by means of either a graphical user interface (GUI) or a batch mode.

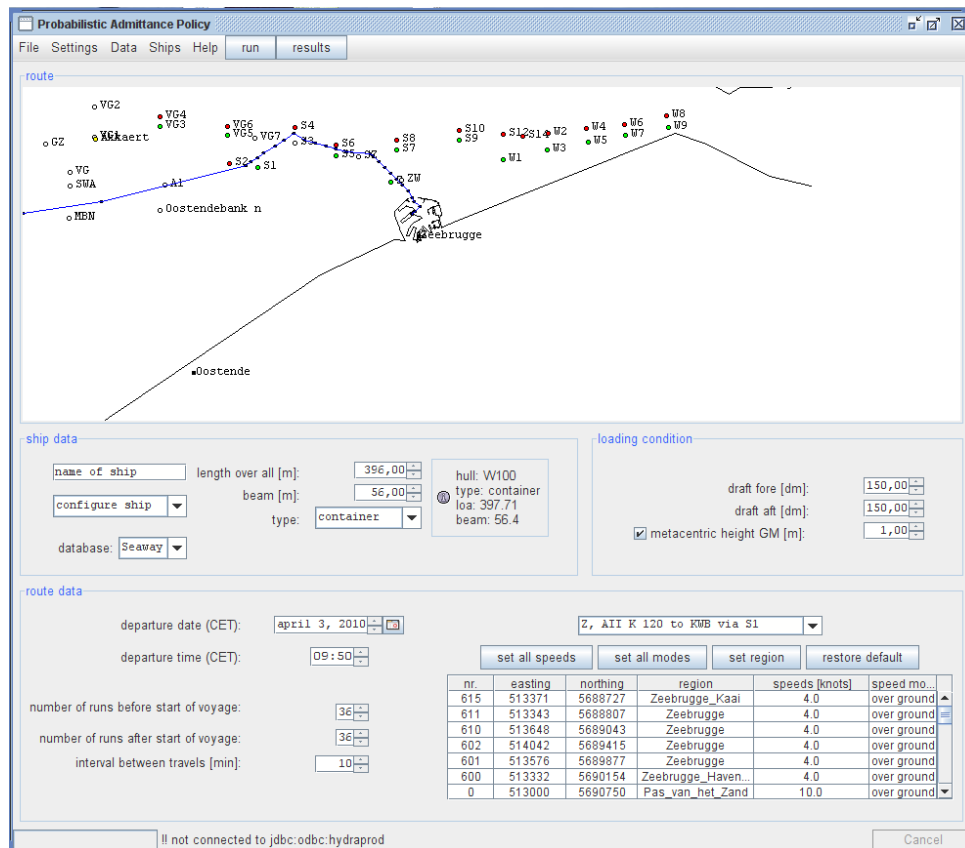


Fig. 2. Graphical user interface for ProToel, showing a map with the selected trajectory. “Ship data” allows either to select a vessel known to the program, or to enter the ship’s main horizontal dimensions and type. Under “Loading condition”, the ship’s draft fore and aft, as well as, optionally, the metacentric height (GM) can be entered. Under “Route data” the user communicates the departure date and times to be considered; the trajectory can be selected and the speed profile can be modified. The menus allow to select the source of hydro/meteo data (local, server, predefined, ...), the method for calculating ship dynamics (response to waves, squat), results format, etc.

C. Output and post-processing

The GUI (see Fig. 2) is more practical for short-term applications (e.g. one or a few tidal cycles with short-term hydro-meteo forecasts) while the batch mode is more appropriate for a long-term (e.g. one year) analysis of tidal windows with the use of either historical data or long-term forecasts (based on astronomical data for the tide).

The bottom data in the trajectory point database consist of nautical bottom depth values and, if applicable, the depth of the water-mud interface. Moreover, a standard deviation can be added to the nautical bottom depth, so that uncertainties of the vertical bottom location can be taken into account in a probabilistic perspective. For some applications, the guaranteed depth, the target depth or the design depth of the different channel stretches may be sufficient, but if required or desired, recent bottom surveys can be interpreted in terms of an average effective bottom and a standard deviation, as suggested by Vantorre et al (2013).

Hydro-meteo data can be generated in different ways. For tidal effects, long-term astronomical data (levels and currents) can be calculated years ahead. On the other hand, wind, waves and the meteorological effects on the tide have a much more limited forecast horizon, and need a continuous update in case the software is used on an operational base. For some studies, a systematic study of wind and wave conditions may be of interest, which justifies the option to select arbitrary values for wind velocity and

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direction, and for Jonswap wave spectrum characteristics such as significant height, mean period and direction. Also the possibility of using historical measurements as input data must be kept.

Depending on their time horizon, the input data can be made available to the program by storing them on either the local computer or on a server. Recent forecasts and measurements of tide, waves, wind and currents are stored in a remote database on a server that can be connected by the user, while a local database may contain long-term predictions.

The output of the computations is stored in xml format and contains all parameters required to check the criteria in all sub-trajectories: gross under keel clearance, penetration into the mud layer, manoeuvrability margin, cross current, probability of bottom touch, etc. The results can be viewed directly in ProToel and exported as a report in pdf format, see Fig. 3. Further post-processing allows to determine tidal windows according to different combinations of criteria, and to account for additional criteria which are not (or not yet) implemented into the main program, e.g. the requirement that the tidal window should comprise a certain point of time related to the tide at a reference location. This post-processing also allows comparison between the length of the tidal window according to different criteria (e.g. probabilistic versus deterministic), and to calculate the fraction of tidal windows for which a certain criterion is dominant.

| region | criteria | threshold | 09:01 CET | 09:11 CET | 09:21 CET | 09:31 CET | 09:41 CET | 09:51 CET | 10:01 CET | 10:11 CET | 10:21 CET | 10:31 CET |
|-----------------------------|--|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Zeetraject | gross UKC towards nautical bottom [%] | 15.0 | 11.5 | 10.9 | 10.4 | 10.0 | 9.7 | 9.5 | 9.4 | 9.4 | 9.3 | 9.2 |
| | gross UKC towards nautical bottom [dm] | 23.0 | 18.0 | 17.0 | 16.0 | 15.0 | 15.0 | 14.0 | 14.0 | 14.0 | 14.0 | 14.0 |
| | route point, time | | 6, 10:38 | 6, 10:48 | 6, 10:58 | 6, 11:08 | 6, 11:18 | 6, 11:28 | 5, 11:28 | 4, 11:24 | 4, 11:24 | 3, 11:27 |
| | manoeuvring margin [%] | 5.0 | 7.2 | 6.5 | 5.8 | 5.3 | 4.9 | 4.6 | 4.5 | 4.4 | 4.3 | 4.4 |
| | manoeuvring margin [dm] | 8.0 | 11.0 | 10.0 | 9.0 | 8.0 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 |
| | route point, time | | 6, 10:38 | 6, 10:48 | 6, 10:58 | 6, 11:08 | 6, 11:18 | 6, 11:28 | 5, 11:28 | 4, 11:24 | 4, 11:24 | 4, 11:34 |
| Pas_van_het_Zand | gross UKC towards nautical bottom [%] | 12.5 | 10.8 | 10.3 | 9.9 | 9.6 | 9.4 | 9.4 | 9.4 | 9.5 | 9.7 | 10.0 |
| | gross UKC towards nautical bottom [dm] | 19.0 | 16.0 | 16.0 | 15.0 | 15.0 | 14.0 | 14.0 | 14.0 | 14.0 | 15.0 | 15.0 |
| | route point, time | | 9, 10:58 | 9, 11:08 | 9, 11:18 | 9, 11:28 | 9, 11:38 | 8, 11:40 | 7, 11:43 | 7, 11:53 | 7, 12:03 | 7, 12:13 |
| | manoeuvring margin [%] | 5.0 | 6.9 | 6.3 | 5.8 | 5.5 | 5.3 | 5.1 | 5.0 | 5.1 | 5.3 | 5.7 |
| | manoeuvring margin [dm] | 8.0 | 10.0 | 10.0 | 9.0 | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 | 9.0 |
| | route point, time | | 9, 10:58 | 9, 11:08 | 9, 11:18 | 9, 11:28 | 8, 11:30 | 8, 11:40 | 8, 11:50 | 8, 12:00 | 8, 12:10 | 8, 12:20 |
| Zeebrugge_Havendammen | gross UKC towards nautical bottom [%] | 12.5 | 11.1 | 10.8 | 10.5 | 10.4 | 10.3 | 10.4 | 10.7 | 11.2 | 11.7 | 12.3 |
| | gross UKC towards nautical bottom [dm] | 19.0 | 17.0 | 16.0 | 16.0 | 16.0 | 16.0 | 16.0 | 16.0 | 17.0 | 18.0 | 19.0 |
| | route point, time | | 10, 11:02 | 10, 11:12 | 10, 11:22 | 10, 11:32 | 10, 11:42 | 10, 11:52 | 10, 12:02 | 10, 12:12 | 10, 12:22 | 10, 12:32 |
| | gross UKC towards top mud layer [%] | -7.0 | -8.5 | -8.9 | -9.2 | -9.3 | -9.3 | -9.2 | -9.0 | -8.5 | -8.0 | -7.3 |
| | gross UKC towards top mud layer [dm] | -11.0 | -13.0 | -14.0 | -14.0 | -14.0 | -14.0 | -14.0 | -14.0 | -13.0 | -12.0 | -11.0 |
| | route point, time | | 10, 11:02 | 10, 11:12 | 10, 11:22 | 10, 11:32 | 10, 11:42 | 10, 11:52 | 10, 12:02 | 10, 12:12 | 10, 12:22 | 10, 12:32 |
| | speed of cross current [kn] | 2.0 | 1.6 | 1.6 | 1.5 | 1.5 | 1.5 | 1.5 | 1.4 | 1.3 | 1.3 | 1.2 |
| | route point, time | | 10, 10:58 | 10, 11:08 | 10, 11:18 | 10, 11:28 | 10, 11:38 | 10, 11:48 | 10, 11:58 | 10, 12:08 | 10, 12:18 | 10, 12:28 |
| | manoeuvring margin [%] | 5.0 | 8.2 | 7.8 | 7.5 | 7.4 | 7.4 | 7.5 | 7.7 | 8.2 | 8.8 | 9.5 |
| | manoeuvring margin [dm] | 8.0 | 12.0 | 12.0 | 11.0 | 11.0 | 11.0 | 12.0 | 12.0 | 13.0 | 13.0 | 14.0 |
| route point, time | | 10, 11:02 | 10, 11:12 | 10, 11:22 | 10, 11:32 | 10, 11:42 | 10, 11:52 | 10, 12:02 | 10, 12:12 | 10, 12:22 | 10, 12:32 | |
| Zeebrugge | gross UKC towards nautical bottom [%] | 10.0 | 9.3 | 9.1 | 9.0 | 9.0 | 9.1 | 9.5 | 9.9 | 10.5 | 11.1 | 11.8 |
| | gross UKC towards nautical bottom [dm] | 15.0 | 14.0 | 14.0 | 14.0 | 14.0 | 14.0 | 14.0 | 15.0 | 16.0 | 17.0 | 18.0 |
| | route point, time | | 13, 11:15 | 13, 11:25 | 13, 11:35 | 13, 11:45 | 13, 11:55 | 13, 12:05 | 13, 12:15 | 13, 12:25 | 13, 12:35 | 13, 12:45 |
| | gross UKC towards top mud layer [%] | -7.0 | -15.2 | -15.5 | -15.7 | -15.7 | -15.6 | -15.4 | -14.9 | -14.4 | -13.8 | -13.1 |
| | gross UKC towards top mud layer [dm] | -11.0 | -23.0 | -24.0 | -24.0 | -24.0 | -24.0 | -23.0 | -23.0 | -22.0 | -21.0 | -20.0 |
| | route point, time | | 12, 11:11 | 12, 11:21 | 12, 11:31 | 12, 11:41 | 12, 11:51 | 12, 12:01 | 12, 12:11 | 12, 12:21 | 12, 12:31 | 12, 12:41 |
| Zeebrugge_Kaai | gross UKC towards nautical bottom [%] | 10.0 | 5.6 | 5.4 | 5.3 | 5.4 | 5.5 | 5.9 | 6.4 | 7.0 | 7.7 | 8.4 |
| | gross UKC towards nautical bottom [dm] | 15.0 | 9.0 | 8.0 | 8.0 | 8.0 | 8.0 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 |
| | route point, time | | 15, 11:17 | 15, 11:27 | 15, 11:37 | 15, 11:47 | 15, 11:57 | 15, 12:07 | 15, 12:17 | 15, 12:27 | 15, 12:37 | 15, 12:47 |
| | gross UKC towards top mud layer [%] | -7.0 | -14.4 | -14.6 | -14.7 | -14.6 | -14.5 | -14.1 | -13.6 | -13.0 | -12.3 | -11.6 |
| | gross UKC towards top mud layer [dm] | -11.0 | -22.0 | -22.0 | -22.0 | -22.0 | -22.0 | -21.0 | -21.0 | -20.0 | -19.0 | -18.0 |
| | route point, time | | 15, 11:17 | 15, 11:27 | 15, 11:37 | 15, 11:47 | 15, 11:57 | 15, 12:07 | 15, 12:17 | 15, 12:27 | 15, 12:37 | 15, 12:47 |
| probability of bottom touch | manoeuvring margin [%] | 5.0 | 2.7 | 2.5 | 2.4 | 2.5 | 2.6 | 3.0 | 3.5 | 4.0 | 4.7 | 5.4 |
| | manoeuvring margin [dm] | 8.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 5.0 | 5.0 | 6.0 | 7.0 | 8.0 |
| | route point, time | | 15, 11:17 | 15, 11:27 | 15, 11:37 | 15, 11:47 | 15, 11:57 | 15, 12:07 | 15, 12:17 | 15, 12:27 | 15, 12:37 | 15, 12:47 |
| | probability of bottom touch | 1.00E-2 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 |

Fig. 3 (continued at next page). Typical ProToel output file, showing sub-trajectories and criteria as a function of departure time. In the presented (fictitious) example, the probability of bottom touch is negligible throughout the considered time span. A deterministic approach based on minimum gross UKC values would result into a tidal window of only 30 minutes (between 12:51 and 13:21), opening when the UKC in the sub-trajectory “Zeetraject” is sufficient and closing due to the current restriction in “Zeebrugge_Havendammen”. In a probabilistic approach combined with a minimum manoeuvring margin, a tidal window of 60 minutes would be available, between 12:21 and 13:21, opening when the penetration in the mud layer in sub-trajectory “Zeebrugge” becomes acceptable. In case of a fluid mud layer with less thickness, the tidal window would even increase to 2:10 hours, opening at 11:11 when the manoeuvring margin at “Zeetraject” becomes sufficient.

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| region | criteria | threshold | 10:41 CET | 10:51 CET | 11:01 CET | 11:11 CET | 11:21 CET | 11:31 CET | 11:41 CET | 11:51 CET | 12:01 CET | 12:11 CET |
|-----------------------------|--|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Zeetraject | gross UKC towards nautical bottom [%] | 15.0 | 9.3 | 9.4 | 9.6 | 9.9 | 10.3 | 10.7 | 11.3 | 11.8 | 12.4 | 13.1 |
| | gross UKC towards nautical bottom [dm] | 23.0 | 14.0 | 14.0 | 15.0 | 15.0 | 16.0 | 16.0 | 17.0 | 18.0 | 19.0 | 20.0 |
| | route point, time | | 3, 11:37 | 3, 11:47 | 3, 11:57 | 3, 12:07 | 3, 12:17 | 3, 12:27 | 3, 12:37 | 3, 12:47 | 3, 12:57 | 3, 13:07 |
| | manoeuvring margin [%] | 5.0 | 4.6 | 4.7 | 4.9 | 5.2 | 5.7 | 6.1 | 6.8 | 7.4 | 8.2 | 9.0 |
| | manoeuvring margin [dm] | 8.0 | 7.0 | 7.0 | 7.0 | 8.0 | 9.0 | 9.0 | 10.0 | 11.0 | 12.0 | 14.0 |
| | route point, time | | 4, 11:54 | 3, 11:47 | 3, 11:57 | 3, 12:07 | 3, 12:17 | 3, 12:27 | 3, 12:37 | 3, 12:47 | 3, 12:57 | 3, 13:07 |
| Pas_van_het_Zand | gross UKC towards nautical bottom [%] | 12.5 | 10.5 | 11.0 | 11.5 | 12.0 | 12.6 | 13.1 | 13.7 | 14.2 | 14.8 | 15.3 |
| | gross UKC towards nautical bottom [dm] | 19.0 | 16.0 | 17.0 | 17.0 | 18.0 | 19.0 | 20.0 | 21.0 | 22.0 | 22.0 | 23.0 |
| | route point, time | | 7, 12:23 | 7, 12:33 | 7, 12:43 | 7, 12:53 | 7, 13:03 | 7, 13:13 | 7, 13:23 | 7, 13:33 | 7, 13:43 | 7, 13:53 |
| | manoeuvring margin [%] | 5.0 | 6.1 | 6.7 | 7.2 | 7.8 | 8.4 | 9.0 | 9.6 | 10.2 | 10.7 | 11.3 |
| | manoeuvring margin [dm] | 8.0 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 | 14.0 | 15.0 | 16.0 | 16.0 | 17.0 |
| | route point, time | | 8, 12:30 | 8, 12:40 | 8, 12:50 | 7, 12:53 | 7, 13:03 | 7, 13:13 | 7, 13:23 | 7, 13:33 | 7, 13:43 | 7, 13:53 |
| Zeebrugge_Havendammen | gross UKC towards nautical bottom [%] | 12.5 | 13.0 | 13.7 | 14.4 | 14.9 | 15.5 | 16.1 | 16.6 | 17.0 | 17.6 | 18.2 |
| | gross UKC towards nautical bottom [dm] | 19.0 | 20.0 | 21.0 | 22.0 | 23.0 | 24.0 | 24.0 | 25.0 | 26.0 | 27.0 | 28.0 |
| | route point, time | | 10, 12:42 | 10, 12:52 | 10, 13:02 | 10, 13:12 | 10, 13:22 | 10, 13:32 | 10, 13:42 | 10, 13:52 | 10, 14:02 | 10, 14:12 |
| | gross UKC towards top mud layer [%] | -7.0 | -6.6 | -5.9 | -5.3 | -4.8 | -4.2 | -3.6 | -3.1 | -2.6 | -2.1 | -1.5 |
| | gross UKC towards top mud layer [dm] | -11.0 | -10.0 | -9.0 | -8.0 | -7.0 | -6.0 | -5.0 | -5.0 | -4.0 | -3.0 | -2.0 |
| | route point, time | | 10, 12:42 | 10, 12:52 | 10, 13:02 | 10, 13:12 | 10, 13:22 | 10, 13:32 | 10, 13:42 | 10, 13:52 | 10, 14:02 | 10, 14:12 |
| | speed of cross current [kn] | 2.0 | 1.1 | 1.0 | 0.8 | 0.5 | 0.3 | 0.1 | 0.1 | 0.3 | 0.6 | 0.8 |
| | route point, time | | 10, 12:38 | 10, 12:48 | 10, 12:58 | 10, 13:08 | 10, 13:18 | 10, 13:28 | 10, 13:38 | 10, 13:48 | 10, 13:58 | 10, 14:08 |
| | manoeuvring margin [%] | 5.0 | 10.3 | 11.1 | 11.7 | 12.3 | 13.0 | 13.5 | 14.0 | 14.5 | 15.1 | 15.7 |
| | manoeuvring margin [dm] | 8.0 | 16.0 | 17.0 | 18.0 | 19.0 | 20.0 | 21.0 | 22.0 | 23.0 | 24.0 | 24.0 |
| Zeebrugge | gross UKC towards nautical bottom [%] | 10.0 | 12.5 | 13.1 | 13.7 | 14.3 | 14.8 | 15.3 | 15.8 | 16.4 | 16.9 | 17.5 |
| | gross UKC towards nautical bottom [dm] | 15.0 | 19.0 | 20.0 | 21.0 | 22.0 | 23.0 | 23.0 | 24.0 | 25.0 | 26.0 | 27.0 |
| | route point, time | | 13, 12:55 | 13, 13:05 | 13, 13:15 | 13, 13:25 | 13, 13:35 | 13, 13:45 | 13, 13:55 | 13, 14:05 | 13, 14:15 | 13, 14:25 |
| | gross UKC towards top mud layer [%] | -7.0 | -12.4 | -11.8 | -11.2 | -10.6 | -10.0 | -9.5 | -9.1 | -8.5 | -7.9 | -7.4 |
| | gross UKC towards top mud layer [dm] | -11.0 | -19.0 | -18.0 | -17.0 | -16.0 | -15.0 | -14.0 | -14.0 | -13.0 | -12.0 | -11.0 |
| | route point, time | | 12, 12:51 | 12, 13:01 | 12, 13:11 | 12, 13:21 | 12, 13:31 | 12, 13:41 | 12, 13:51 | 12, 14:01 | 12, 14:11 | 12, 14:21 |
| Zeebrugge_Kaai | gross UKC towards nautical bottom [%] | 10.0 | 9.0 | 9.6 | 10.2 | 10.8 | 11.3 | 11.8 | 12.3 | 12.9 | 13.4 | 14.0 |
| | gross UKC towards nautical bottom [dm] | 15.0 | 14.0 | 15.0 | 15.0 | 16.0 | 17.0 | 18.0 | 19.0 | 20.0 | 20.0 | 21.0 |
| | route point, time | | 15, 12:57 | 15, 13:07 | 15, 13:17 | 15, 13:27 | 15, 13:37 | 15, 13:47 | 15, 13:57 | 15, 14:07 | 15, 14:17 | 15, 14:27 |
| | gross UKC towards top mud layer [%] | -7.0 | -11.0 | -10.4 | -9.8 | -9.2 | -8.7 | -8.2 | -7.7 | -7.2 | -6.6 | -6.0 |
| | gross UKC towards top mud layer [dm] | -11.0 | -17.0 | -16.0 | -15.0 | -14.0 | -13.0 | -12.0 | -12.0 | -11.0 | -10.0 | -9.0 |
| | route point, time | | 15, 12:57 | 15, 13:07 | 15, 13:17 | 15, 13:27 | 15, 13:37 | 15, 13:47 | 15, 13:57 | 15, 14:07 | 15, 14:17 | 15, 14:27 |
| Zeebrugge | gross UKC towards nautical bottom [%] | 10.0 | 18.2 | 19.0 | 19.9 | 20.9 | 22.2 | 23.7 | 25.2 | 26.9 | 28.7 | 30.6 |
| | gross UKC towards nautical bottom [dm] | 15.0 | 28.0 | 29.0 | 30.0 | 32.0 | 34.0 | 36.0 | 38.0 | 41.0 | 44.0 | 46.0 |
| | route point, time | | 13, 14:35 | 13, 14:45 | 13, 14:55 | 13, 15:05 | 13, 15:15 | 13, 15:25 | 13, 15:35 | 13, 15:45 | 13, 15:55 | 13, 16:05 |
| | gross UKC towards top mud layer [%] | -7.0 | -6.8 | -6.0 | -5.1 | -4.2 | -3.0 | -1.5 | -0.1 | 1.6 | 3.4 | 5.2 |
| | gross UKC towards top mud layer [dm] | -11.0 | -10.0 | -9.0 | -8.0 | -6.0 | -5.0 | -2.0 | 0.0 | 2.0 | 5.0 | 8.0 |
| | route point, time | | 12, 14:31 | 12, 14:41 | 12, 14:51 | 12, 15:01 | 12, 15:11 | 12, 15:21 | 12, 15:31 | 12, 15:41 | 12, 15:51 | 12, 16:01 |
| Zeebrugge_Kaai | gross UKC towards nautical bottom [%] | 10.0 | 14.7 | 15.6 | 16.4 | 17.5 | 18.9 | 20.3 | 21.9 | 23.7 | 25.5 | 27.3 |
| | gross UKC towards nautical bottom [dm] | 15.0 | 22.0 | 24.0 | 25.0 | 27.0 | 29.0 | 31.0 | 33.0 | 36.0 | 39.0 | 41.0 |
| | route point, time | | 15, 14:37 | 15, 14:47 | 15, 14:57 | 15, 15:07 | 15, 15:17 | 15, 15:27 | 15, 15:37 | 15, 15:47 | 15, 15:57 | 15, 16:07 |
| | gross UKC towards top mud layer [%] | -7.0 | -5.3 | -4.4 | -3.6 | -2.5 | -1.1 | 0.3 | 1.9 | 3.7 | 5.5 | 7.3 |
| | gross UKC towards top mud layer [dm] | -11.0 | -8.0 | -7.0 | -5.0 | -4.0 | -2.0 | 1.0 | 3.0 | 6.0 | 8.0 | 11.0 |
| | route point, time | | 15, 14:37 | 15, 14:47 | 15, 14:57 | 15, 15:07 | 15, 15:17 | 15, 15:27 | 15, 15:37 | 15, 15:47 | 15, 15:57 | 15, 16:07 |
| probability of bottom touch | | 1.00E-2 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 |

| region | criteria | threshold | 12:21 CET | 12:31 CET | 12:41 CET | 12:51 CET | 13:01 CET | 13:11 CET | 13:21 CET | 13:31 CET | 13:41 CET | 13:51 CET |
|-----------------------------|--|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Zeetraject | gross UKC towards nautical bottom [%] | 15.0 | 13.6 | 14.3 | 14.9 | 15.5 | 16.2 | 16.9 | 17.6 | 18.4 | 19.4 | 20.4 |
| | gross UKC towards nautical bottom [dm] | 23.0 | 21.0 | 22.0 | 23.0 | 24.0 | 25.0 | 26.0 | 27.0 | 28.0 | 29.0 | 31.0 |
| | route point, time | | 3, 13:17 | 3, 13:27 | 3, 13:37 | 3, 13:47 | 3, 13:57 | 3, 14:07 | 3, 14:17 | 3, 14:27 | 3, 14:37 | 3, 14:47 |
| | manoeuvring margin [%] | 5.0 | 9.7 | 10.4 | 11.1 | 11.8 | 12.4 | 13.1 | 13.8 | 14.6 | 15.5 | 16.4 |
| | manoeuvring margin [dm] | 8.0 | 15.0 | 16.0 | 17.0 | 18.0 | 19.0 | 20.0 | 21.0 | 22.0 | 24.0 | 25.0 |
| | route point, time | | 3, 13:17 | 3, 13:27 | 3, 13:37 | 3, 13:47 | 3, 13:57 | 3, 14:07 | 3, 14:17 | 3, 14:27 | 3, 14:37 | 3, 14:47 |
| Pas_van_het_Zand | gross UKC towards nautical bottom [%] | 12.5 | 15.9 | 16.4 | 17.1 | 17.7 | 18.5 | 19.4 | 20.5 | 21.7 | 23.0 | 24.5 |
| | gross UKC towards nautical bottom [dm] | 19.0 | 24.0 | 25.0 | 26.0 | 27.0 | 28.0 | 29.0 | 31.0 | 33.0 | 35.0 | 37.0 |
| | route point, time | | 7, 14:03 | 7, 14:13 | 7, 14:23 | 7, 14:33 | 7, 14:43 | 7, 14:53 | 7, 15:03 | 7, 15:13 | 7, 15:23 | 7, 15:33 |
| | manoeuvring margin [%] | 5.0 | 11.8 | 12.3 | 12.8 | 13.4 | 14.1 | 14.9 | 15.8 | 16.8 | 18.0 | 19.2 |
| | manoeuvring margin [dm] | 8.0 | 18.0 | 19.0 | 19.0 | 20.0 | 21.0 | 23.0 | 24.0 | 26.0 | 27.0 | 29.0 |
| | route point, time | | 7, 14:03 | 7, 14:13 | 7, 14:23 | 7, 14:33 | 7, 14:43 | 7, 14:53 | 7, 15:03 | 7, 15:13 | 7, 15:23 | 7, 15:33 |
| Zeebrugge_Havendammen | gross UKC towards nautical bottom [%] | 12.5 | 18.7 | 19.4 | 20.2 | 21.0 | 22.0 | 23.2 | 24.7 | 26.2 | 27.8 | 29.6 |
| | gross UKC towards nautical bottom [dm] | 19.0 | 28.0 | 29.0 | 31.0 | 32.0 | 33.0 | 35.0 | 37.0 | 40.0 | 42.0 | 45.0 |
| | route point, time | | 10, 14:22 | 10, 14:32 | 10, 14:42 | 10, 14:52 | 10, 15:02 | 10, 15:12 | 10, 15:22 | 10, 15:32 | 10, 15:42 | 10, 15:52 |
| | gross UKC towards top mud layer [%] | -7.0 | -1.0 | -0.3 | 0.5 | 1.3 | 2.3 | 3.5 | 5.0 | 6.5 | 8.2 | 10.0 |
| | gross UKC towards top mud layer [dm] | -11.0 | -1.0 | 0.0 | 1.0 | 2.0 | 3.0 | 5.0 | 8.0 | 10.0 | 12.0 | 15.0 |
| | route point, time | | 10, 14:22 | 10, 14:32 | 10, 14:42 | 10, 14:52 | 10, 15:02 | 10, 15:12 | 10, 15:22 | 10, 15:32 | 10, 15:42 | 10, 15:52 |
| | speed of cross current [kn] | 2.0 | 1.0 | 1.2 | 1.5 | 1.3 | 0.9 | 1.3 | 2.2 | 2.8 | 3.3 | 3.6 |
| | route point, time | | 10, 14:18 | 10, 14:28 | 10, 14:38 | 10, 14:48 | 10, 14:58 | 10, 15:08 | 10, 15:18 | 10, 15:28 | 10, 15:38 | 10, 15:48 |
| | manoeuvring margin [%] | 5.0 | 16.3 | 16.9 | 17.7 | 18.6 | 19.5 | 20.7 | 22.1 | 23.6 | 25.3 | 27.0 |
| | manoeuvring margin [dm] | 8.0 | 25.0 | 26.0 | 27.0 | 28.0 | 30.0 | 31.0 | 34.0 | 36.0 | 38.0 | 41.0 |
| Zeebrugge | gross UKC towards nautical bottom [%] | 10.0 | 18.2 | 19.0 | 19.9 | 20.9 | 22.2 | 23.7 | 25.2 | 26.9 | 28.7 | 30.6 |
| | gross UKC towards nautical bottom [dm] | 15.0 | 28.0 | 29.0 | 30.0 | 32.0 | 34.0 | 36.0 | 38.0 | 41.0 | 44.0 | 46.0 |
| | route point, time | | 13, 14:35 | 13, 14:45 | 13, 14:55 | 13, 15:05 | 13, 15:15 | 13, 15:25 | 13, 15:35 | 13, 15:45 | 13, 15:55 | 13, 16:05 |
| | gross UKC towards top mud layer [%] | -7.0 | -6.8 | -6.0 | -5.1 | -4.2 | -3.0 | -1.5 | -0.1 | 1.6 | 3.4 | 5.2 |
| | gross UKC towards top mud layer [dm] | -11.0 | -10.0 | -9.0 | -8.0 | -6.0 | -5.0 | -2.0 | 0.0 | 2.0 | 5.0 | 8.0 |
| | route point, time | | 12, 14:31 | 12, 14:41 | 12, 14:51 | 12, 15:01 | 12, 15:11 | 12, 15:21 | 12, 15:31 | 12, 15:41 | 12, 15:51 | 12, 16:01 |
| Zeebrugge_Kaai | gross UKC towards nautical bottom [%] | 10.0 | 14.7 | 15.6 | 16.4 | 17.5 | 18.9 | 20.3 | 21.9 | 23.7 | 25.5 | 27.3 |
| | gross UKC towards nautical bottom [dm] | 15.0 | 22.0 | 24.0 | 25.0 | 27.0 | 29.0 | 31.0 | 33.0 | 36.0 | 39.0 | 41.0 |
| | route point, time | | 15, 14:37 | 15, 14:47 | 15, 14:57 | 15, 15:07 | 15, 15:17 | 15, 15:27 | 15, 15:37 | 15, 15:47 | 15, 15:57 | 15, 16:07 |
| | gross UKC towards top mud layer [%] | -7.0 | -5.3 | -4.4 | -3.6 | -2.5 | -1.1 | 0.3 | 1.9 | 3.7 | 5.5 | 7.3 |
| | gross UKC towards top mud layer [dm] | -11.0 | -8.0 | -7.0 | -5.0 | -4.0 | -2.0 | 1.0 | 3.0 | 6.0 | 8.0 | 11.0 |
| | route point, time | | 15, 14:37 | 15, 14:47 | 15, 14:57 | 15, 15:07 | 15, 15:17 | 15, 15:27 | 15, 15:37 | 15, 15:47 | 15, 15:57 | 15, 16:07 |
| probability of bottom touch | | 1.00E-2 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 | 0.00E0 |

Fig. 3. (continued)

4. TYPICAL APPLICATIONS

A. *Short-term determination of tidal windows for deep-drafted ships*

Determination of tidal windows for deep-drafted vessels on a short-term basis (e.g. 24 or 48 hours) requires recent bottom surveys, as well as reliable forecasts for waves (directional spectra), tidal levels and tidal currents. For the coastal channels, such forecasts are updated continuously by the Flemish Hydrography on the server of Flanders Hydraulics Research, and made available in a format suitable for ProToel within the intranet of the Department of Mobility and Public Works of the Flemish Government. A validation phase for the software is planned for vessels to and from Zeebrugge, first to evaluate the systematic application of ProToel taking account of the present deterministic criteria with respect to under keel clearance, mud penetration and cross current, and secondly to assess the effects of a probabilistic approach on the accessibility of the port.

For assessing the deterministic criteria, only bottom, tide and current data have to be available, while a probabilistic policy also requires wave data. Moreover, a probabilistic approach requires data concerning the ship response to waves and squat, while for a deterministic approach only the ship's draft and the speed profile are required.

B. *Long-term accessibility predictions*

The batch mode allows long-term calculations over a period of typically one year to determine the length of the tidal windows for each tidal cycle for a vessel with a specified draft (or draft range) moving through the channel with a given speed profile. In practice, a tidal window is only accepted if its length exceeds a minimum value (e.g. 30 or 60 minutes). Post-processing allows to determine the percentage of tidal cycles for which a tidal window with sufficient length is available over the year as a function of draft. For such a long-term prediction, only astronomical tide data can be used, so that only deterministic criteria based on gross UKC and tidal currents can be applied. This type of application was performed for container carriers arriving at and departing from the port of Antwerp during the different stages of the latest deepening program of the river Scheldt.

C. *Comparison between access policies*

The application of a probabilistic access policy principally leads to a more optimal use of the channel compared to a deterministic one, as the tidal window is expected to be extended in favourable weather conditions, while the channel will only be less accessible in case the probability of bottom touch is unacceptable. The ProToel batch mode can be used to assess the impact of switching between policies on the length of the tidal windows and other relevant performance parameters, by recalculating the tidal windows for a period (e.g. one year) in the past making use of historic hydro/meteo measurements.

As an example, Fig. 4 compares the length of tidal windows according to different sets of criteria, e.g. deterministic versus probabilistic criteria, based on measured hydro/meteo data during a full year for the same type of vessel in a range of loading conditions following a given trajectory with a specified speed profile. Points located above the first bisector indicate that the second set of criteria results into a longer tidal window compared to the first set. Apparently, in the example displayed in Fig. 4, this is the case for a majority of tidal cycles. On the other hand it is also clear that the opposite is true for a small fraction of the tidal cycles; criteria set 1 even does not allow any traffic in a limited number of tidal cycles, unlike criteria set 2.

Statistical post-processing allows to express the results in terms of percentiles for each of the sets of criteria considered. The results may be used to support a decision to modify the governing access criteria.

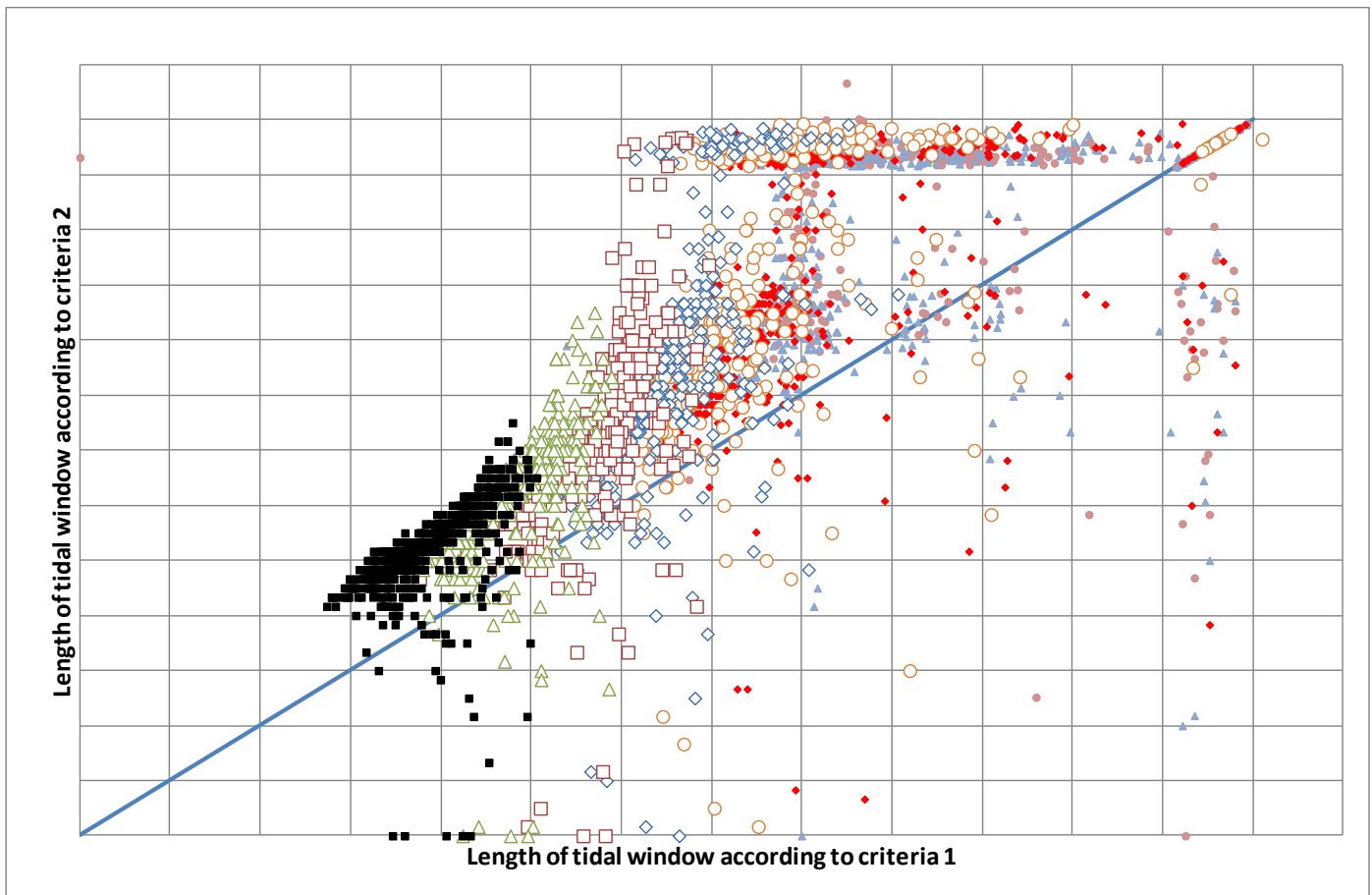


Fig. 4. Comparison between tidal windows for the same type of ship at a given trajectory with the same speed profile, fulfilling different sets of criteria. Hydro/meteo data are based on historic measurements during a full year. The symbols refer to different draft values.

5. PRESENT AND FURTHER DEVELOPMENTS

At present, a number of additional effects are being implemented in the ProToel software: wind effects and effects of centrifugal forces in a bend. Both effects cause a heel angle, which affects the vertical position of the points at the ship's side. Both effects contain a steady term, and can therefore be simplified to a constant heel angle, but wind fluctuations and transient effects in bends cause heel angle variations which should be accounted for in a probabilistic approach.

Other developments under consideration concern the implementation of a bottom survey. A distinction should be made between the water depth taken into account for squat calculation and assessment of the manoeuvrability margin on one hand, and for bottom touch probability on the other. Roughly, the average bottom depth is relevant for hydrodynamic topics (squat, manoeuvring) but ship-bottom contact assessment requires the introduction of an 'effective' bottom consisting of the most shallow points of grid cells with dimensions that are relevant compared to ship dimensions (e.g. $50 * 10 \text{ m}^2$); this effective bottom can be reduced to an average value over a sub-trajectory and a standard deviation (Vantorre et al., 2013).

Finally a next step in the development of ProToel as an operational support tool concerns an maximisation of the tidal window by means of the selection of an optimal speed profile over the trajectory, as well as other features to support waterway authorities and pilots in their decisions.

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