OPTIMISATION OF TIDAL WINDOWS FOR DEEP-DRAFTED VESSELS BY MEANS OF A PROBABILISTIC APPROACH POLICY FOR ACCESS CHANNELS WITH DEPTH LIMITATIONS

by

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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 and other complicating factors can be based on either deterministic or probabilistic principles. For determining tidal windows for deep-drafted vessels arriving at and departing from the ports located at the Belgian coast and the Western Scheldt estuary, a software tool ProToel has been developed, which can take account of several criteria including gross under keel clearance, probability of bottom touch, manoeuvrability margin, current restrictions, penetration into mud layers. After an overview of the software and some typical applications, a recent study of the feasibility of the introduction of a probabilistic access policy for container and bulk traffic to/from Flushing, Antwerp and Terneuzen will be discussed. In general, the introduction of a probabilistic access policy would have a favourable effect on the accessibility of the ports in terms of maximum allowable draft and/or length of the tidal window. Compared to a deterministic approach, however, the decision-making algorithm for a probabilistic access policy appears to depend on a significantly larger number of parameters, which moreover often induce a greater degree of uncertainty in the results.

Keywords: Ports and maritime navigation, deep-draft navigation and waterways, probabilistic approach policy, tidal windows, access channels

1. INTRODUCTION

In January 2014, MarCom report 121 entitled “Harbour Approach Channels – Design Guidelines” was issued (PIANC, 2014), providing guidelines and recommendations for the design of vertical and horizontal dimensions of harbour approach channels and manoeuvring and anchoring areas. In comparison with the PIANC-IAPH (1997) report “Approach Channels – A Guide for Design” which the new publication supersedes and replaces, guidelines for establishing depth requirements have received particular attention. The selection of an adequate channel depth during the design phase has important consequences for the (capital and maintenance) dredging costs, but also will determine the accessibility of the channel during its entire lifetime. Indeed, the available water depth will determine the maximum allowable draft, as a minimum under keel clearance is required to compensate for the ship’s vertical motions and therefore to prevent the ship from bottom contact, but also to guarantee sufficient manoeuvrability.

During several stages in channel design, the required vertical margin can be quantified in a deterministic or in a probabilistic way. For channels which are subject to wave action, somehow probabilistic aspects will always be included – explicitly or implicitly – in the determination of the required depth, through the stochastic character of the waves. In addition, other factors contributing to the relative position between the ship’s keel and the bottom – such as the tidal elevation, the ship’s draft, the ship’s squat, the ship’s vertical motion due to wind and bends, the position of the bottom – may be subject to uncertainty which is preferably taken into consideration in a probabilistic way.

While a channel designer can only take into account long-term statistics and forecasts with respect to the hydro-meteo conditions and prognoses with respect to the evolution of shipping traffic, waterway authorities need to take decisions for a medium long or short period and are confronted with sometimes unexpected trends in the shipping world. For this reason, the link between channel design and channel operation is not always straightforward, although the criteria have the same goal: preventing the ship from touching the bottom and from insufficient controllability. While the designer

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needs to consider the accessibility of the channel over its entire lifetime, the channel operator has to take a decision for each individual arriving and departing ship.

Irrespective of the way it has been designed, the access policy for an existing channel can be based on either deterministic or probabilistic criteria. With respect to the vertical aspects, a deterministic policy is usually based on a minimum gross under keel clearance, expressed as a percentage of the ship's draft, the value of which is selected in such a way that the probability of bottom touch will be acceptably small for all vessels making use of the channel in non-exceptional conditions. If this value does not depend on relevant hydro-meteo parameters, e.g. wave conditions, the prescribed under keel clearance is only required in adverse weather conditions, and might be considered as sub-optimal in case of beneficial conditions. A probabilistic access policy, based on an acceptable probability of bottom touch during the transit of any (deep-drafted) vessel, could therefore result into a more optimal use of the channel.

For the management of the shipping traffic to the Dutch and Belgian ports located at the Western Scheldt estuary and the river Scheldt – Flushing (Vlissingen), Terneuzen, Ghent (Gent), Antwerp (Antwerpen) – a Common Nautical Authority is responsible, in which both the Netherlands and the Flemish region of Belgium are represented. The effect of switching from the present deterministic access policy to a probabilistic approach for these ports was recently investigated by Ghent University and Flanders Hydraulics Research by order of the Common Nautical Authority. Before focusing on the results of this study, the paper will discuss the criteria – of both deterministic and probabilistic nature – commonly applied for transits through access channels which are subject to tidal windows, and provide a general overview of the background, theoretical principles an database structure of the software package called ProToel, which was used to perform the calculations. The results of the study for the (Western) Scheldt harbours will raise some points of special interest on the implementation of a probabilistic approach policy.

2. LIMITING CRITERIA FOR TRANSIT THROUGH ACCESS CHANNELS

2.1 General

The purpose of this chapter is to provide an overview of criteria that are commonly used to guarantee safe transit of deep-drafted ships through shallow channels in areas which are subject to tidal action. Two types of criteria – some of which may be ship type dependent – can be distinguished:

- criteria which aim to avoid contact of the ship with either the bottom or overhead structures;
- criteria which aim to avoid unsafe manoeuvres.

Criteria can be formulated in a deterministic or a probabilistic way. Each of the criteria will be discussed below, focusing on the present situation of shipping traffic to the Belgian seaports and the Dutch Western Scheldt ports. Therefore, contact with overhead structures will not be covered.

2.2 Contact avoidance criteria

The vertical distance between the ship's keel and the bottom depends on a number of factors related to the ship, the water level and the bottom (PIANC, 2014).

Ship related factors include:

- the ship's loading condition (draft aft, amidships and fore, including hogging/sagging effects) in still water conditions, which may be variable due to density variations over the ship's passage through the channel;
- the vertical motion (sinkage and trim) of the ship due to squat, which depends on the ship's horizontal motion through the water (hence influenced by currents), the water depth, the channel cross section, the ship's geometry, the ship's propulsion;
- the vertical ship motions due to heel induced by centrifugal forces in bends;
- the vertical ship motions (heave, pitch, roll) induced by waves;
- the vertical ship motions due to heel induced by wind.

Water level dependent factors are – at least in maritime access channels connecting a port with the open sea – mainly caused by tidal effects. The latter are principally driven by astronomic phenomena, but may be significantly influenced by meteorological effects (air pressure, winds, …).

Bottom related factors, finally, are linked with the bottom characteristics, which are determined by the bottom material, the local morphology, the maintenance program (e.g. dredging schedules), …, but also the way bathymetric surveys are executed and interpreted is of importance.

The most straightforward way to formulate a criterion to avoid bottom contact consists of selecting a minimum gross under keel clearance value (i.e. the difference between the local and instantaneous water depth and the static draft in still water), expressed either in metre or as a percentage of the ship's draft in still water. Such a deterministic formulation offers the advantage that the amount of information required to determine tidal windows is rather restricted: the bottom depth over the trajectory, the tidal elevation over the trajectory (or at least at the shallow sections) as a function of time, and the ship's draft. Assumptions may be considered to simplify the calculation, e.g. by accounting for the guaranteed depth levels instead of the actual ones, except for the zones where the guaranteed depth is not met, or by considering the fresh water draft for trajectories with variable water density. As such, simplifications generally imply a more conservative approach and they will result into a suboptimal exploitation of the channel.

A deterministic gross under keel clearance (UKC) criterion is nowadays applied in the channels giving access to the ports located at the Flemish coast and along the river Scheldt, shown in Figure 1. The following values are currently used: 15.0% of draft for *Scheur West* (SW) and *Scheur East* (SO), 12.5% of draft for *Pas van het Zand* (PZ) and the Dutch part of the *Western Scheldt* (WS), 10.0% of draft for the Scheldt river (SC) on Belgian territory, 10% for the Zeebrugge outer harbour (OH) area (i.e. within the breakwaters) and 1.0 m for the Sea Canal from Terneuzen to Ghent. For LNG carriers arriving at or departing from Zeebrugge, larger minimum values for the under keel clearances are applied: 20% for *Scheur West* and *Pas van het Zand* and 15% for the Zeebrugge outer harbour. It is worth mentioning that the method used for determining the bottom level depends on the bottom conditions. In the Zeebrugge outer harbour area and parts of the *Pas van het Zand*, where the bottom is covered by a fluid mud layer, the 1200 kg/m³ density level is considered to be the *nautical bottom*. On the other hand, in the *Scheur West/Oost* channels the bottom level is based on the average of multi-beam survey data over square grid cells of 3 * 3 m² (Vantorre et al., 2013).

A probabilistic approach policy, on the other hand, requires the selection of a value for an acceptable probability of bottom-ship contact during the transit of one single vessel. Mostly an acceptable probability for an undesired event is based on an acceptable return period, which has to be selected taking account of the consequences of such a bottom touch. Eventually it is not the probability, but the risk (= probability * consequence) which has to be limited. Acceptable return periods recommended by Puertos del Estado (1999) with respect to access channel design may vary between 15 and 800 years, depending on the type of channel (general navigation channel versus specific industrial channel), the channel bed condition (hard, medium, soft) and the character of the risk of loss of human life or environmental damages (low, medium, high risk). Assuming low risk and a soft channel bed, 25 years seems to be an acceptable return period for a general navigation channel. The yearly number of transits of sea-going ships through the access channels in the Belgian coastal area and the Western Scheldt estuary is approximately 80 000 (Anon, 2011), of which about 800 are restricted by a tidal window; a 25 years return period therefore is equivalent with an acceptable bottom touch probability of $5 \cdot 10^{-5}$. As will be explained in section 4.4, for only less than 50% of the ships restricted by the tide the probability of bottom touch (PBT) will be the determining criterion, so that a value of 10^{-4} appears to be acceptable.

Comparable values for both the return period and the probability of bottom touch can be found in literature (PIANC, 2014). According to van de Kaa (1984), suitable criteria for ship-channel bed contact are 10^{-4} and 10^{-2} for accidents per passage under average and extreme environmental conditions, respectively. Dand and Lyon (1993) mention a probability of grounding of $3 \cdot 10^{-5}$, based on accident statistics. The approach criteria for the access to the Port of Rotterdam are also based on a 25 years return period for a (significant) bottom touch, and resulted into an acceptable probability of bottom contact of about $1.6 \cdot 10^{-4}$ (Savenije, 1996).

Figure 1: Access channels to the Belgian coastal sea ports and the Belgian and Dutch (Western) Scheldt ports. (Courtesy Maritime Access Division, Flemish Government: http://www.maritiemetoegang.be/)

2.3 Controllability criteria

A probability of bottom touch criterion needs to be accompanied by an additional criterion to guarantee the manoeuvrability and controllability of the vessel, as these properties are significantly affected with decreasing under keel clearance. Such a criterion can be formulated in terms of either an minimum gross under keel clearance (UKC) or a minimum manoeuvrability margin (MM). The latter is defined as the time-averaged clearance under the ship, incorporating the effects of water depth, draft, squat, heel, but excluding the higher-frequency oscillatory effects caused by wave action, as the latter are assumed not to have a major adverse effect on the manoeuvring and steering behaviour. PIANC (2014) suggests a minimum manoeuvrability margin of 5% of draft or 0.6 m, whichever is greater. The manoeuvrability margin criterion will overrule the probability of bottom touch criterion in case of favourable wave conditions in the channels at sea, or in areas protected from wave impact such as rivers and sheltered estuaries.

Specific controllability criteria may be required in navigation areas the bottoms of which are covered with fluid mud layers. For instance, in the outer harbour of Zeebrugge (see Figure 2), an additional operational condition is applied 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 for manoeuvring container carriers with suitable tug assistance.

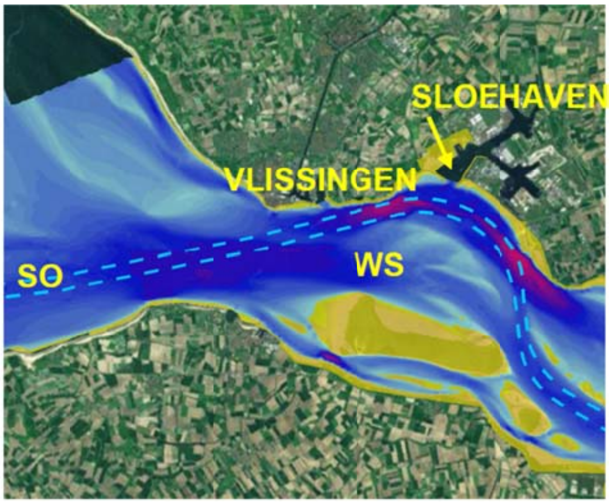


Figure 2 (left): Port of Zeebrugge with access channel *Pas van het Zand* (PZ), breakwaters and outer harbour (OH). (Source: http://maritiemetoegang.be/zeebrugge)

Figure 3 (right): Vlissingen (Flushing) with access channels *Scheur Oost* (SO) and *Western Scheldt* (WS).

Figure 4: Port of Antwerp: access to Zandvliet/Berendrecht Locks and Deurganck Dock via *Western Scheldt* (WS) and *Scheldt* (SC).

At locations with considerable variable, mostly tidal driven, cross currents, safe transit may only be possible during a fraction of the tidal cycle during which the current conditions are acceptable. Related criteria may be linked to a maximum value of the cross current; as an example, arrival or departure of LNG carriers to the Port of Zeebrugge (see Figure 2) 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, 2013). For other vessels, 2 knots is considered to be the limit for arrival or departure.

As an alternative way of formulating current windows, often the passage time at critical waypoints is subject to limitations with reference to the tidal cycle. For instance, a tidal window for bulk carriers with destination Antwerp – Berendrecht Lock (see Figure 4) is only accepted if it contains a specific point in time with respect to high water at a certain location (e.g. 60 minutes past High Water at Prosperpolder, near the Belgian-Dutch border). Similarly, the entrance of Sloehaven (Flushing, see Figure 3) with bulk carriers is only possible if the tidal window comprises the point in time defined by 70 minutes past High Water at Flushing.

2.4 Sets of criteria

Often the use of an access channel is only allowed if a combination of criteria is fulfilled. In a deterministic approach, the main criterion is formulated as a minimum value for the gross under keel clearance with respect to the (nautical) bottom, expressed as a percentage of draft. For some trajectories and/or traffics, additional controllability criteria have to be imposed as well, such as a current criterion and/or a mud penetration criterion.

In a probabilistic approach, the minimum gross UKC value will be overruled by a criterion based on an acceptable bottom contact probability. While the same controllability criteria as mentioned above will remain valid, an additional manoeuvrability margin criterion will be required as well.

In Table 1, the present (deterministic) criteria applied nowadays for allowing inbound and outbound bulk and container traffic to the (Western) Scheldt ports are listed, as well as the alternative set of criteria that has been considered. Although not investigated yet, the present set of criteria for container traffic to and from Zeebrugge is summarized in Table 2, together with an alternative set which could be the base for a probabilistic access policy.

Trajectory	Traffic	Deterministic policy	Probabilistic policy
Flushing inbound	Bulk	SO/SW: UKC > 15% WS: UKC > 10% Current window Vlissingen Tidal window > 30 min	PBT < 1 E-04 MM > 5% Current window Vlissingen Tidal window > 30 min
Flushing outbound	Bulk	SO/SW: UKC > 15% WS: UKC > 10% Tidal window > 30 min	PBT < 1 E-04 MM > 5% Tidal window > 30 min
Terneuzen inbound	Bulk	SO/SW: UKC > 15% WS: UKC > 12.5% Tidal window > 60 min	PBT < 1 E-04 MM > 5% Tidal window > 60 min
Terneuzen outbound	Bulk	SO/SW: UKC > 15% WS: UKC > 12.5% Tidal window > 60 min	PBT < 1 E-04 MM > 5% Tidal window > 60 min
Antwerp inbound	Bulk	SO/SW: UKC > 15% WS: UKC > 12.5% SC: UKC > 10% Current window Prosperpolder Tidal window > 60 min	PBT < 1 E-04 MM > 5% Current window Prosperpolder Tidal window > 60 min
Antwerp outbound	Bulk	SO/SW: UKC > 15% WS: UKC > 12.5% SC: UKC > 10% Tidal window > 60 min	PBT < 1 E-04 MM > 5% Tidal window > 60 min
Flushing inbound	Container	SO/SW: UKC > 15% WS: UKC > 10% Tidal window > 30 min	PBT < 1 E-04 MM > 5% Tidal window > 30 min
Flushing outbound	Container	SO/SW: UKC > 15% WS: UKC > 10% Tidal window > 30 min	PBT < 1 E-04 MM > 5% Tidal window > 30 min
Antwerp inbound	Container	SO/SW: UKC > 15% WS: UKC > 12.5% SC: UKC > 10% Tidal window > 60 min	PBT < 1 E-04 MM > 5% Tidal window > 60 min
Antwerp outbound	Container	SO/SW: UKC > 15% WS: UKC > 12.5% SC: UKC > 10% Tidal window > 60 min	PBT < 1 E-04 MM > 5% Tidal window > 60 min

Table 1: Selected combinations of deterministic and probabilistic criteria for inbound and outbound bulk and container traffic to the (Western) Scheldt ports

Trajectory	Traffic	Deterministic policy	Probabilistic policy
Zeebrugge inbound	Container	SO/SW: UKC > 15% PZ: UKC > 12.5% OH: UKC(nb) > 10% OH: UKC(mud) > -7% Current window Zeebrugge	PBT < 1 E-04 MM > 5% OH: UKC(nb) > 10% OH: UKC(mud) > -7% Current window Zeebrugge
Zeebrugge outbound	Container	SO/SW: UKC > 15% PZ: UKC > 12.5% OH: UKC(nb) > 10% OH: UKC(mud) > -7% Current window Zeebrugge	PBT < 1 E-04 MM > 5% OH: UKC(nb) > 10% OH: UKC(mud) > -7% Current window Zeebrugge

Table 2: Selected combinations of deterministic and probabilistic criteria for inbound and outbound container traffic to Zeebrugge (not investigated)

3. CALCULATION TOOL

3.1 Background

ProToel is a software application for determining tidal windows for deep-drafted vessels arriving at or departing from the ports located at the Belgian coast or in the (Western) Scheldt estuary: Zeebrugge, Flushing, Terneuzen, Antwerp. Although specifically developed for probabilistic admittance policy calculations, additional criteria can be taken into account, which allows either to combine probabilistic and deterministic criteria or to make comparisons between different access policies. ProToel was developed by Ghent University (Maritime Technology Division) in close co-operation with Flanders Hydraulics Research on behalf of the Flemish government.

The ProToel software is developed in an object oriented programming environment, making use of Java, and can be run by either a graphical user interface or in batch mode. The program allows a user to select a ship with a specific loading condition, a route to be followed with a specified speed profile (either over ground or through the water) along the trajectory, and a specific starting time (or a series of starting times) 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).

3.2 Databases

ProToel requires the availability of a number of internal or external databases.

The ship database contains squat data (sinkage and trim tables) and wave response characteristics (directional response amplitude operators in frequency domain for heave, pitch and roll) for a broad range of ship types (slender and full), main dimensions, loading conditions (draft and metacentric height), forward speeds and under keel clearances. The database is based on model test results from the towing tank for manoeuvres in shallow water (co-operation Flanders Hydraulics Research – Ghent University) and on calculations with seakeeping software. This database can be extended to other ship types or specific ships if required. As an example, Figure 5 shows a comparison between one specific curve from the ProToel database with the result of a large number of empirical squat formulae and recent observations on bulk carriers bound for Sloehaven.

The trajectory and trajectory points database contains bottom data: the (average) depth of the (nautical) bottom with respect to LAT, a standard deviation on the bottom level, the level of the mud-water interface. Depending on the application, the database may contain guaranteed or target levels, design levels or recent bottom survey data for the different channel stretches.

Finally, the hydro-meteo database contains data for a number of locations as a function of time: tidal elevation, current speed and direction, directional wave spectra, water density, wind. Depending on the application, this database contains long-term forecasts (e.g. astronomic tide and current), short-term forecasts, or measured (historic) data. In case of short-term operational use, the forecasts have to be updated on a regular base, so that in this case the data files are imported from a remote database on a server. If historic data are used, the required information is usually stored in a local database.

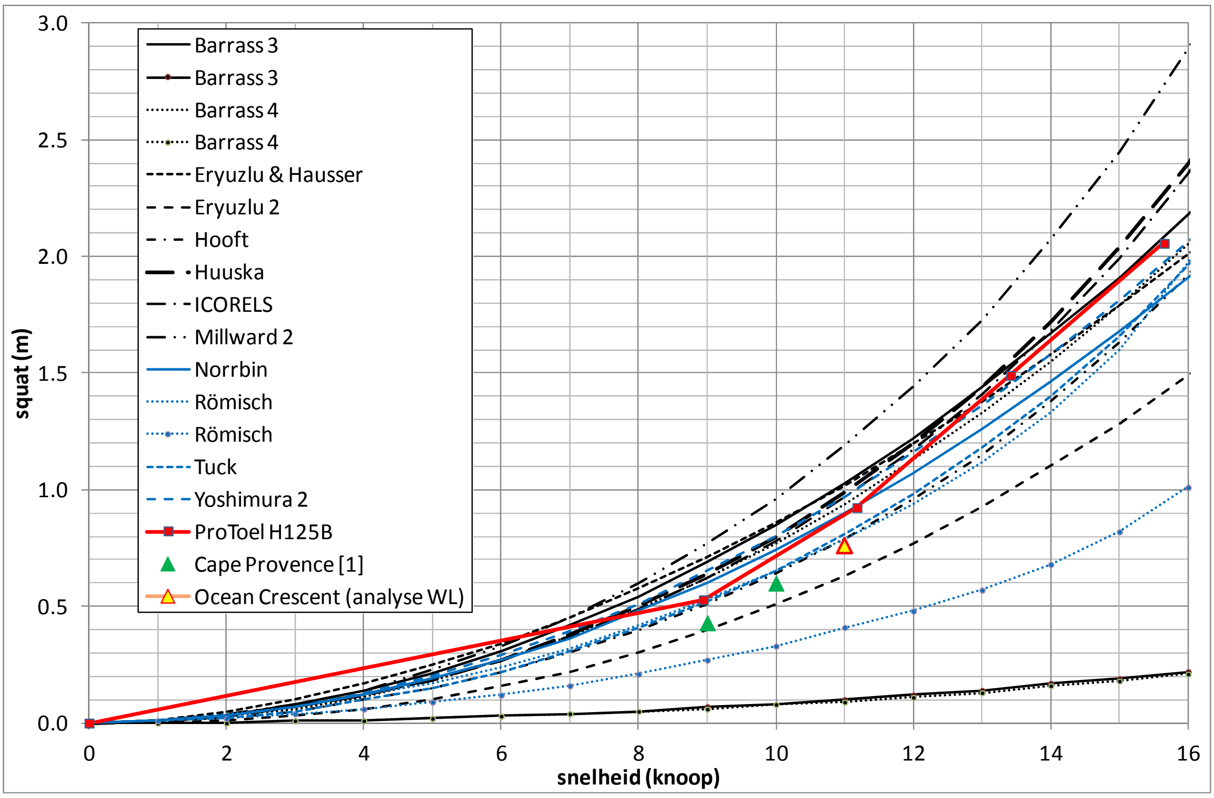


Figure 5: Maximum squat as a function of speed for bulk carrier H125 of the ProToel database, draft 14.5 m, gross UKC 25%. For Barrass 3 and 4 the minimum sinkage is displayed as well. Remark: the Millward2 method was developed for slender ships and is therefore not applicable.

3.3 Output data

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 Figure 6. 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 in 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.

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, or that a tidal window is only acceptable if its length exceeds a minimum value (e.g. 30 or 60 minutes). 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		5, 10:38	6, 10:48	6, 10:58	6, 11:08	6, 11:18	6, 11:28	5, 11:28	4, 11:24	4, 11:34	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		5, 10:38	6, 10:48	6, 10:58	6, 11:08	6, 11:18	6, 11:28	5, 11:28	4, 11:24	4, 11:34	4, 11:44
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	11.0	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
	manoeuvring margin [%]	5.0	6.3	6.1	6.0	6.0	6.1	6.4	6.9	7.5	8.2	8.9
	manoeuvring margin [dm]	8.0	10.0	9.0	9.0	9.0	9.0	10.0	10.0	11.0	12.0	14.0
	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
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
	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

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	21.0	22.0	23.0	24.0
	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
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
	manoeuvring margin [%]	5.0	9.7	10.4	11.0	11.6	12.2	12.8	13.3	13.8	14.4	15.0
	manoeuvring margin [dm]	8.0	15.0	16.0	17.0	18.0	19.0	19.0	20.0	21.0	22.0	23.0
	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
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	-7.1	-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
	manoeuvring margin [%]	5.0	6.0	6.6	7.2	7.8	8.4	8.9	9.5	10.1	10.7	11.3
	manoeuvring margin [dm]	8.0	9.0	10.0	11.0	12.0	13.0	14.0	14.0	15.0	16.0	17.0
	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
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

Figure 6. (continued at next page)

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
	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
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
	manoeuvring margin [%]	5.0	15.7	16.6	17.4	18.4	19.7	21.2	22.7	24.4	26.1	27.9
	manoeuvring margin [dm]	8.0	24.0	25.0	26.0	28.0	30.0	32.0	34.0	37.0	40.0	42.0
	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
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
	manoeuvring margin [%]	5.0	12.1	13.0	13.9	15.0	16.4	17.9	19.5	21.2	23.0	24.7
	manoeuvring margin [dm]	8.0	18.0	20.0	21.0	23.0	25.0	27.0	30.0	32.0	35.0	38.0
	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

Figure 6: Typical ProToel output file, showing sub-trajectories and criteria as a function of departure time.

4. Comparison between deterministic and probabilistic access policies

4.1 Background

On the one hand the present deterministic access policy has proved to be sufficiently safe, but on the other hand it is presumed that in some cases the margin can be reduced without increasing the overall risk. Reduction of the margin may not only have economic benefits, such as potentially larger tidal windows and/or increased drafts, but it would also allow to spread the transits of deep-draughted vessels more evenly over the tidal cycle.

In order to assess the potential benefits and the impact of a switch from the present deterministic policy to a version based on probabilistic principles, the Common Nautical Authority (represented by Rijkswaterstaat Zeeland) commissioned Ghent University and Flanders Hydraulics Research to compare both access policies for deep-drafted container ships and bulk carriers to and from Flushing, Terneuzen and Antwerp. Based on historic hydro-meteo data of 2011, a comparison was made between the deterministic and probabilistic tidal windows that could have been assigned to the mentioned types of vessel on the different trajectories for a range of drafts for each tidal cycle. For this purpose, the different criteria were assessed by means of ProToel for each combination of trajectory, ship type and draft for consecutive departure times with a 10 minutes interval. The calculation results were post-processed to tidal windows for 683 tidal cycles of 2011.

4.2 Input data

The trajectories and ship types considered for this study are listed in Table 1; departure point for all inbound ships and arrival point for all outbound ships is the Wandelaar Pilot Station. For each trajectory and ship type, the main ship dimensions and the draft range were selected as shown in Table 3. The code refers to the ship in the ProToel database. The horizontal dimensions of the bulk carriers for Flushing are based on the present traffic to Sloehaven. For Antwerp, the dimensions correspond with the largest bulk carriers that have entered the Berendrecht Lock, while for Terneuzen/Ghent so-called Kamsarmax type bulkers are considered, having the maximum beam allowed to the present Terneuzen West Lock. The two types of container carriers were at the start of the study the largest ones that had been received by the port of Antwerp; in the meantime, also a ship with a length over all of 399 m and a beam of 59 m has berthed at the Deurganck Dock terminals.

Trajectory and traffic	Length over all (m)	Beam (m)	Draft (dm)	Code
Bulk to/from Vlissingen	289	45	160 – 174	H125
Bulk to/from Terneuzen/Gent	229.5	37	135 – 150	H115
Bulk to/from Antwerpen	335	52	145 – 159	E100
Container to/from Vlissingen	397 365	56 51.2	145 – 159	W100 W092
Container to/from Antwerpen	397 365	56 51.2	145 – 159	W100 W092

Table 3: Main characteristics for ships selected for analysis

The hydro-meteo data used as input for the study are historic data from 2011. Wave data is available through HMCZ (Hydro Meteo Centre Zeeland) for the Dutch territory, while the Flemish Banks Monitoring Network delivered data for the Belgian part, see Figure 7. As ProToel requires directional wave spectra, it was preferred to use directly data from directional wave buoys (KWI, BVH) or combine non-directional spectra from wave buoys close to the channels (SWI, HNTE) with directional data from another buoy nearby (CAD). Although waves upstream Vlissingen are not expected to affect the tidal windows, wave data from several locations on the Western Scheldt (HNTE, OVHW, OVVA) were used, in combination with an assumed directional spreading. For all these locations data were available with time intervals of 30 minutes.

Figure 7: Selected locations for wave spectra: Kwintebank (KWI), Bol van Heist (BVH), Scheur-Wielingen (SWI), Cadzand (CAD), Honte (HNTE), Overloop van Hansweert (OVHW), Overloop van Valkenisse (OVVA).

The data for tidal elevations and currents used in this study were based on astronomic calculations, not on measured data. The data were delivered by HMCZ with time intervals of 10 minutes for a large number of locations along the trajectories. Current velocities are of specific importance for this study due to the effect on squat, which depends on the speed of the vessel through the water.

The effect of the water density along the trajectories – though of importance for traffic for Terneuzen and Antwerp – is not taken into consideration. If fresh water drafts are considered for these trajectories, the results are at the safe side.

For the bottom levels along the trajectories, use is made of the target depths for maintenance dredging, except for the locations where the channel is naturally deeper.

The ship's speed profile along the trajectory is also of great importance, due to the relative velocity with respect to the tidal wave, and because of the direct relation between speed (through water) and squat. The speed profiles for inbound and outbound bulk carriers and container ships are based on the IVS database. Average speeds over the sea and river sub-trajectories are shown in Table 4.

	Bulk carriers		Container carriers	
	inbound	outbound	inbound	outbound
Sea	10.6 knots	10.8 knots	12.3 knots	15.1 knots
River	11.2 knots	9.3 knots	13.2 knots	12.5 knots

Table 4: Average speeds over ground of inbound and outbound bulk carriers and container ships on the sea and river sub-trajectories.

4.3 Results

Within this paper, two cases will be discussed more extensively: inbound bulk carriers with destination Flushing – Sloehaven, and container carriers departing from Antwerp – Deurganck Dock.

For each of the 683 tidal cycles analysed in this study, the tidal window according to the present access policy and a possible future probabilistic access policy were calculated for ships with varying draft. If the length of the tidal windows obtained with both policies are individually compared, a graph as shown in Figure 8 can be plotted. Each symbol located above the first bisector corresponds with a tidal cycle during which a probabilistic access policy would result into a longer tidal window, while symbols under the first bisector corresponds with tidal cycles with a less advantageous result in case of a switch to a probabilistic policy. Apparently, the effect is advantageous for the majority of the tidal windows in case of the bulk carriers to Flushing - Sloehaven, although in some rare cases a probabilistic approach leads to a shorter tidal window, or a ship would not be allowed under a probabilistic policy while it would be assigned a tidal window on a deterministic base. The latter is the case for the symbols located on the abscissa axis. Also for the container traffic with departure from Antwerp, a beneficial effect on the tidal window length of the introduction of a probabilistic access policy can be observed in the majority of the tidal cycles, although also the number of cycles for which ships cannot leave the harbour at the given draft is somewhat higher compared to the former case.

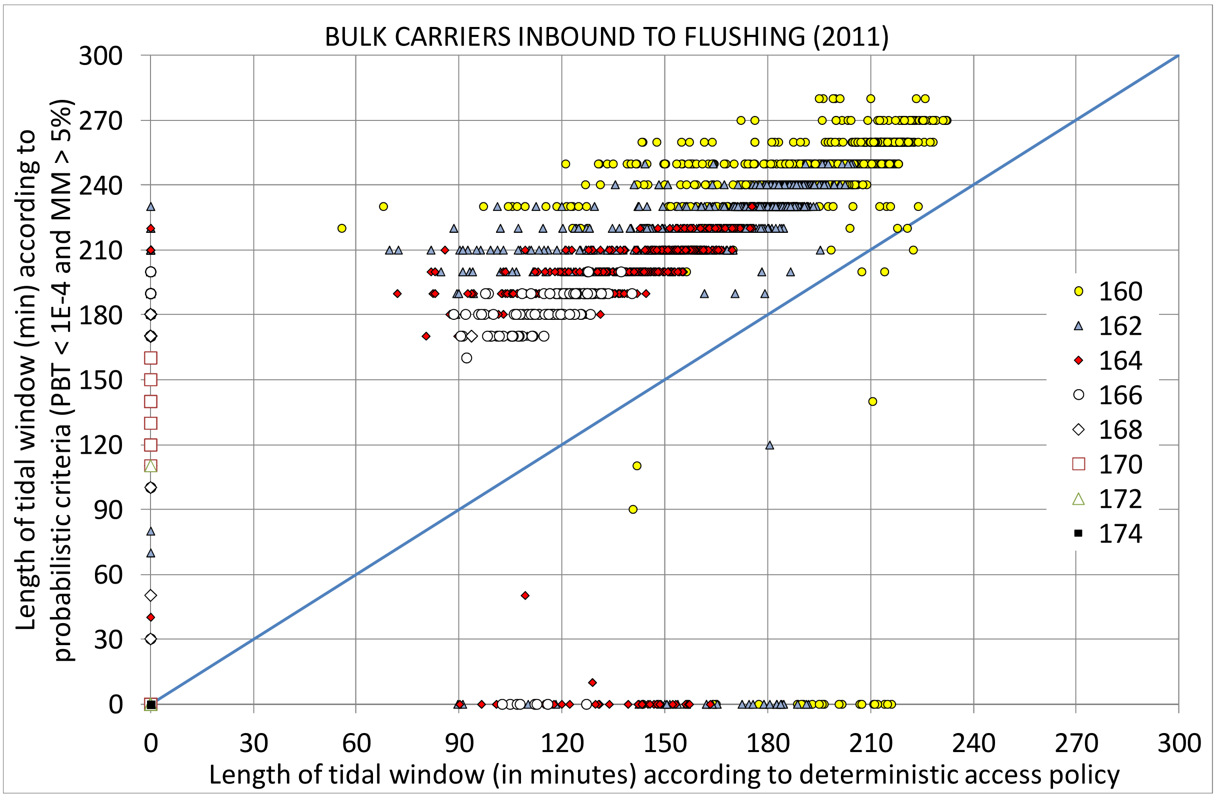
In Figure 9, the 10 and 90% percentile values for the length of the tidal windows according to different sets of criteria are plotted as a function of draft. The transition from a deterministic (circles) to a probabilistic (triangles) policy, as described in Table 1, would clearly have a beneficial effect on the length of the tidal windows, and on the maximum allowable draft. The graphs also illustrate the importance of the manoeuvrability margin criterion that has to be fulfilled in combination with the probability of bottom touch criterion: in case no account would be taken of the MM criterion, the percentiles (squares) for the tidal window length would increase significantly. On the other hand, the effect of the allowable value for the PBT is rather limited, as the curves based on a 10^{-4} and 10^{-2} probability values (full versus dotted lines) nearly coincide, due to the relatively high tidal level gradient.

Figure 9 allows to determine the maximum draft for which a tidal window is available in 90% of the tidal cycles according to the deterministic and probabilistic policies. Table 5 summarizes the results for all considered traffics and trajectories; for the other cases the maximum draft exceeds the investigated draft range.

	bulk carriers inbound to Flushing Sloehaven (H125)	bulk carriers outbound from Flushing Sloehaven (H125)	bulk carriers outbound from Antwerp Deurganck Dock (E100)	container carriers outbound from Antwerp Deurganck Dock (W100)	container carriers outbound from Antwerp Deurganck Dock (W092)
Deterministic	163.4	162.9	148.0	153.7	153.7
Probabilistic	165.6	168.0	151.0	157.0	156.3

Table 5: Maximum draft (dm) resulting into a tidal window in 90% of the tidal cycles according to deterministic and probabilistic access policy.

The fraction of the tidal cycles for which a tidal window can be assigned according to the different sets of criteria is shown in Figure 10 (black curves). A transition from the present deterministic policy to a probabilistic approach would in general cause a significant increase of this fraction, except for the lower draft range. As an example, for bulk traffic to Flushing - Sloehaven, an inbound ship with a draft of 16.5 m would receive a tidal window in less than 50% of the tidal cycles according to the present policy, while this percentage would increase to more than 90% with a probabilistic policy. On the other hand, a ship with a draft of 16 m would be assigned a deterministic window in 100% of the cycles, which would be reduced to 97% in a probabilistic approach. Similar conclusions can be drawn for outbound container carriers leaving Antwerp, where a probabilistic policy turns out to be quite advantageous in the draft range above 15.3 m. Figure 10 also illustrates the importance of the manoeuvring margin, especially in the larger draft range. Finally, the red curves in Figure 10 show in which percentage of the tidal cycles a policy switch would lead to a longer tidal window (corresponding with the symbols above the first bisector in Figure 8); the values are typically 95 to 100%.



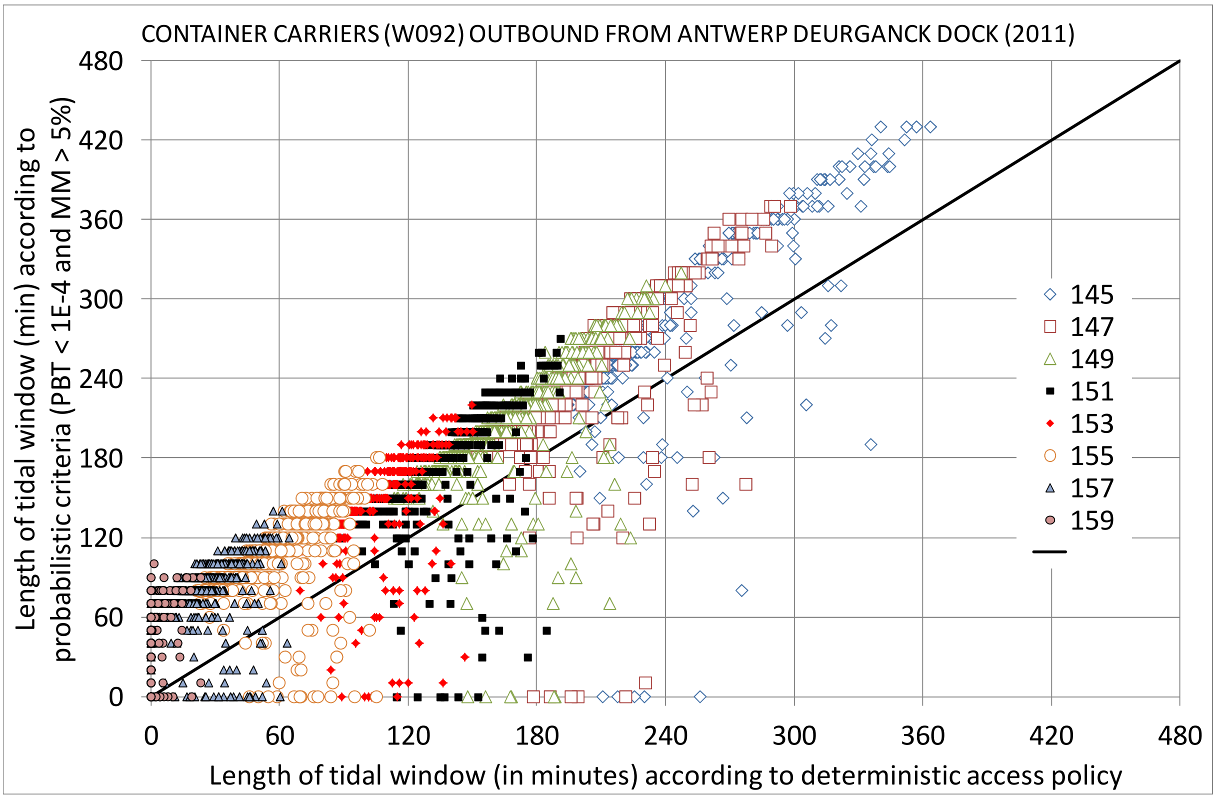
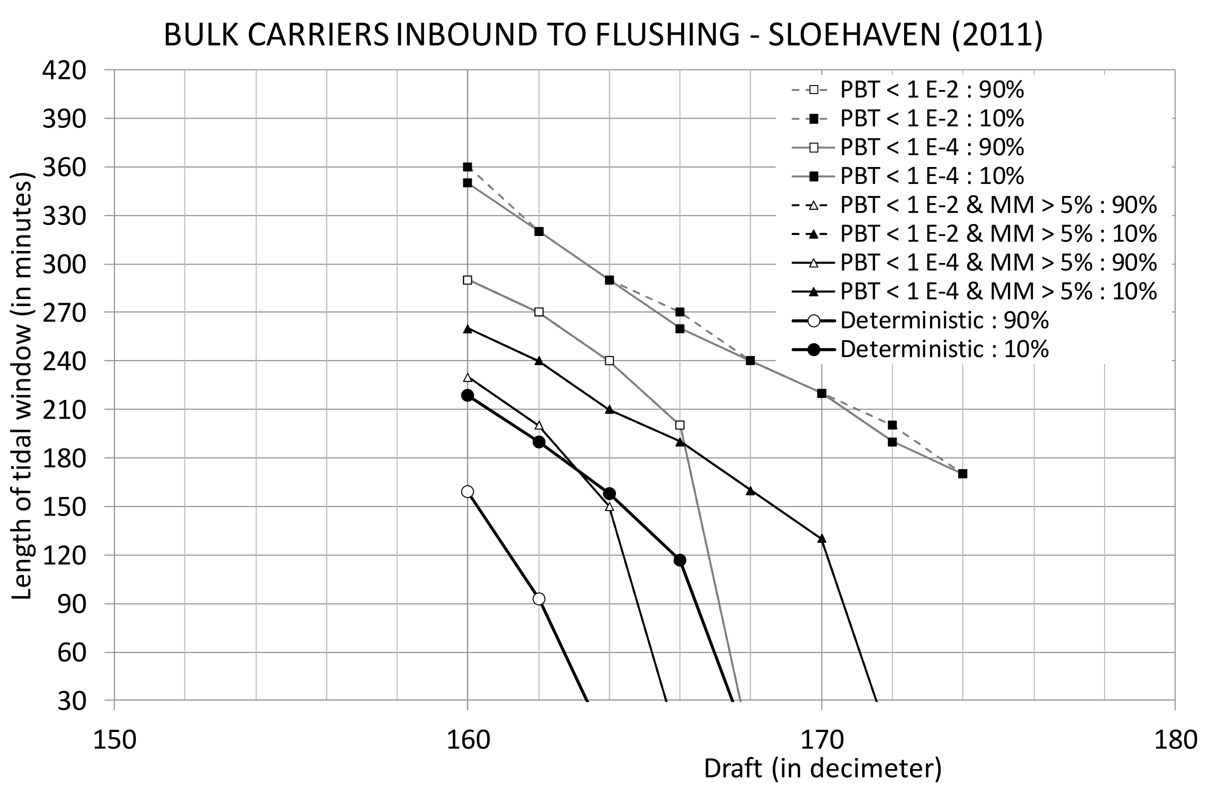


Figure 8: Comparison between length of tidal windows according to the present access policy and to a probabilistic access policy, for different draft values (in decimeter). Above: bulk carriers (H125) inbound to Flushing – Sloehaven; below: container carriers (W092) outbound from Antwerp – Deurganck Dock.



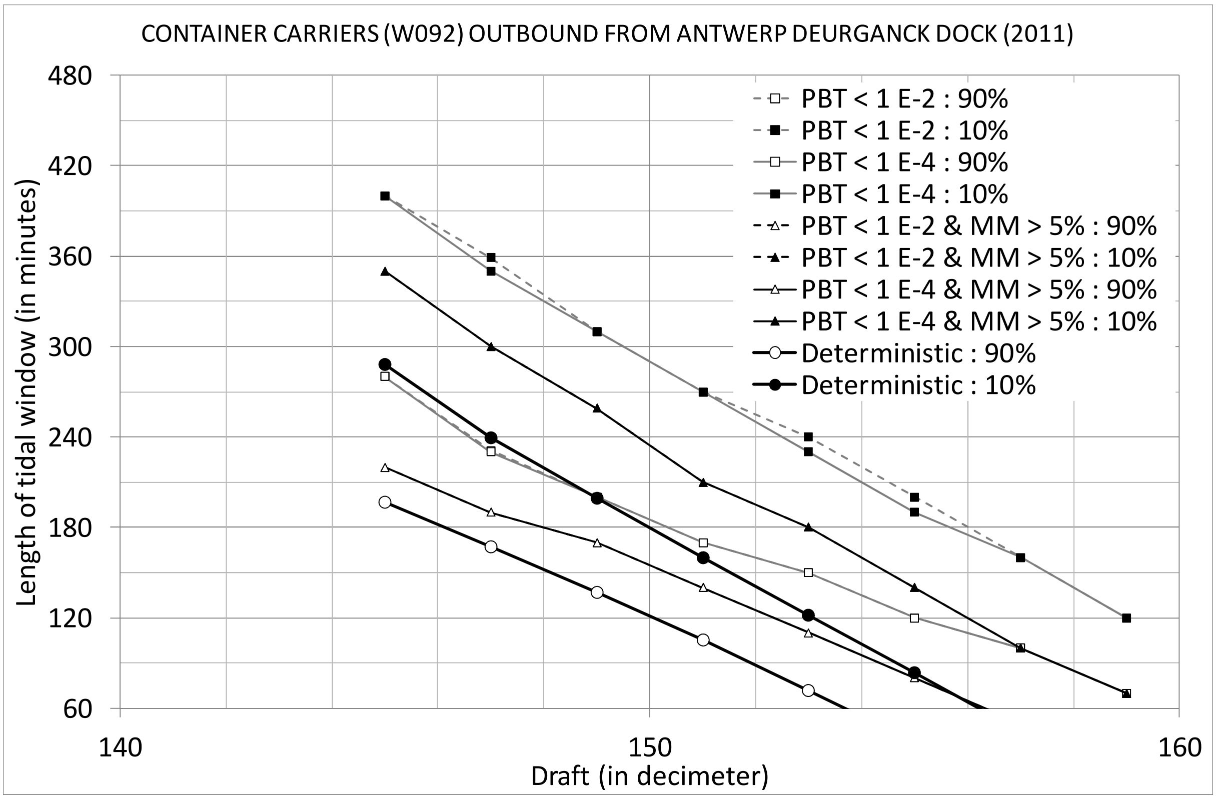
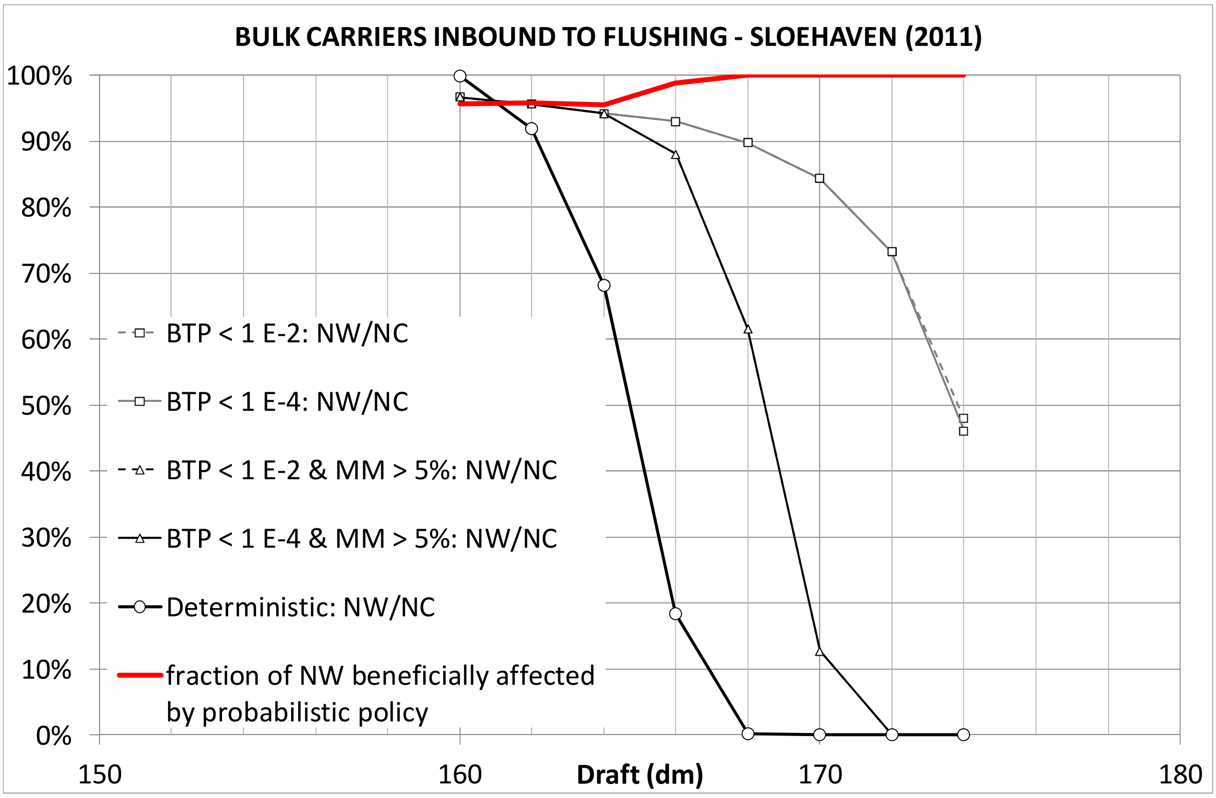


Figure 9: Length of tidal windows according to several sets of criteria: percentiles 10% and 90% as a function of draft. Above: bulk carriers (H125) inbound to Flushing – Sloehaven; below: container carriers (W092) outbound from Antwerp – Deurganck Dock.



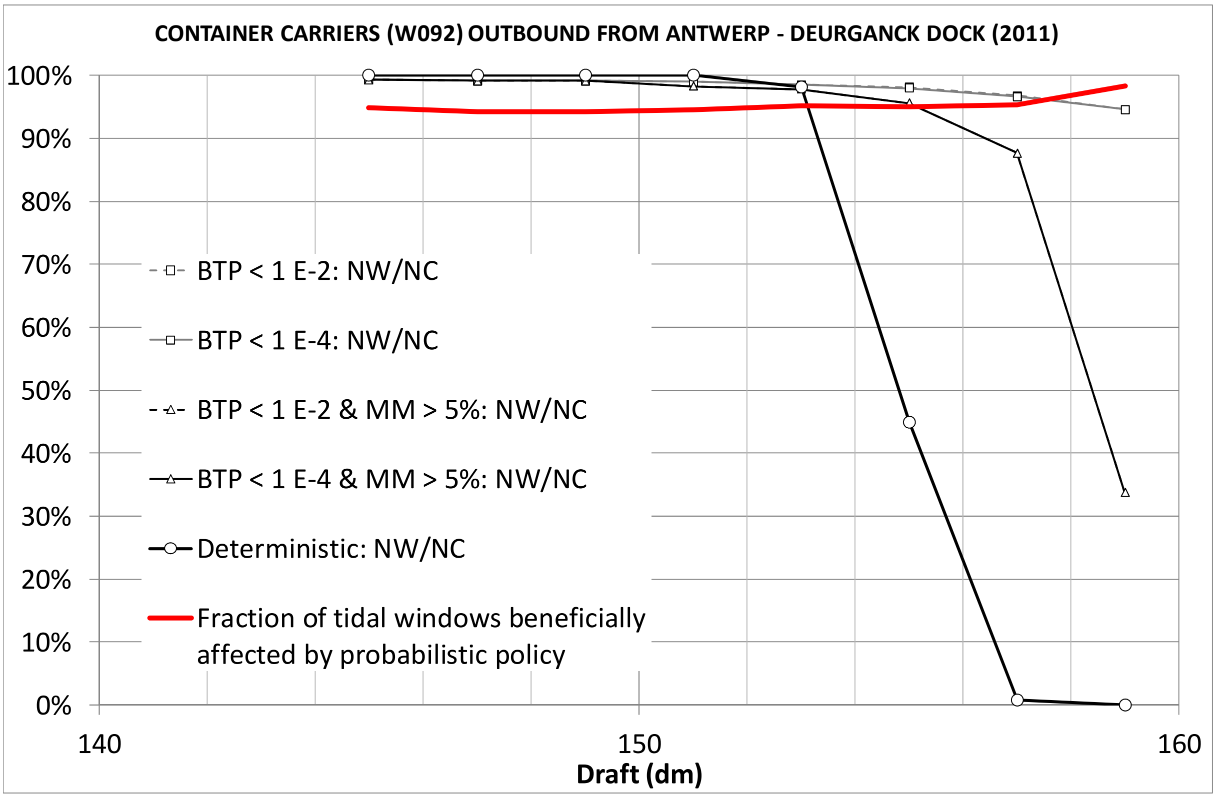


Figure 10: Fraction of the tidal cycles for which a probabilistic access policy results into a longer tidal window (red curve); percentage of tidal cycles for which a tidal window can be assigned according to different sets of criteria (NW = number of tidal windows; NC = number of tidal cycles). Above: bulk carriers (H125) inbound to Flushing – Sloehaven; below: container carriers (W092) outbound from Antwerp – Deurganck Dock.

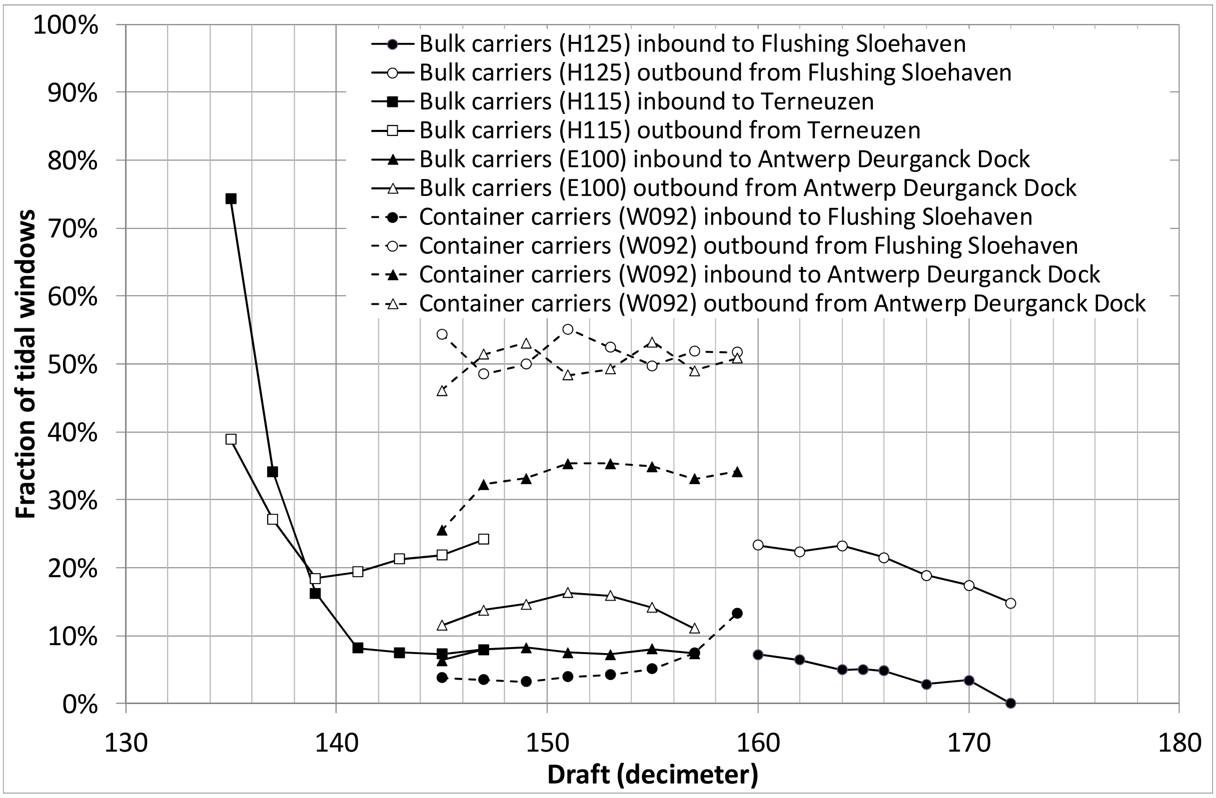


Figure 11: Fraction of the tidal windows for which the opening or closing time is determined by the probability of bottom touch.

The importance of the manoeuvrability margin criterion has already been mentioned,and is confirmed by Figure 11. For inbound bulk carriers with destination Flushing - Sloehaven, the tidal window is determined by the probability of bottom touch in less than 10% of the cycles; this percentage decreases with increasing draft. For outbound container carriers leaving Antwerp Deurganck Dock, this fraction may increase to about 50%. This might be surprising, as the MM will always be dominant on the river sub-trajectory. On the other hand, the PBT criterion will be increasingly important on the sea sub-trajectory with decreasing draft.

4.4 Discussion: probability of bottom touch

In section 2.2, the allowed probability of bottom touch based on a return period of 25 years was estimated to be $5 \cdot 10^{-5}$, based on 800 deep-drafted ships per year. On the other hand, the results of the study have revealed that the PBT is the dominant criterion for opening or closing the tidal window in only a fraction of the tidal cycles; in many cases, the manoeuvrability margin, a local current criterion or the duration of the tidal window are more important. A conservative estimation of the yearly number ships for which the probability of bottom touch would be the most important criterion, based on the results of the study discussed above, is about 350. The critical PBT of 10^{-4} which was used in the study is reached if the number of ships the tidal window of which is determined by the PBT criterion is 400 per year.

Moreover, within reasonable limits the selection of a critical PBT value appears to be of limited importance, as the tidal level difference within the 10 minutes interval between two voyages calculated with ProToel mostly leads to a sharp increase or decrease of the PBT.

5. Conclusions and recommendations

The comparison between probabilistic and deterministic tidal windows led to the following conclusions:

- Compared to the present deterministic access policy, criteria based on a probability of bottom touch in combination with a minimum manoeuvrability margin result in a clear increase of the accessability of the ports involved, both in terms of length of tidal window and maximum allowable draft.

- In spite of the overall improvement, a probabilistic approach leads to reduced tidal window in a limited number (less than 5%) of tidal cycles; in some exceptional cases a probabilistic policy would not allow a ship to enter the approach channnel while a tidal window would be assigned in case of a deterministic policy.
- In a significant fraction of the tidal cycles, the limits of the tidal window are not determined by th PBT criterion, but by the MM criterion.
- The effect of the selected PBT value appeared to be marginal, even in those cases for which the PBT criterion is dominant.
- The dominance of the MM criterion implies the importance of the minimum value, for which 5% of draft was selected, as recommended by PIANC (2014).

A number of recommendations can be formulated as well:

- A reliable and accurate estimation of squat is of great importance, taking account of the effect of squat on both the probability of bottom touch and the manoeuvrability margin. The use of state-of-the-art position measuring systems for determining squat on board of vessels could contribute to an increased knowledge about squat.
- In principle, the manoeuvrability margin, for which a minimum value of 5% of draft was selected in this study, should be determined accounting for the specific conditions in which a reduced MM value occurs and for the required manoeuvring characteristics in these circumstances.
- Accuracy and reliability of tidal elevations as a function of time and location are essential for both a deterministic and a probabilistic access policy.
- Other phenomena affecting the under keel clearance and the probability of bottom touch should be accounted for: density variations, wind, bends, stability parameters (GM).
- The actual bottom bathymetry should be accounted for in a probabilistic approach.

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