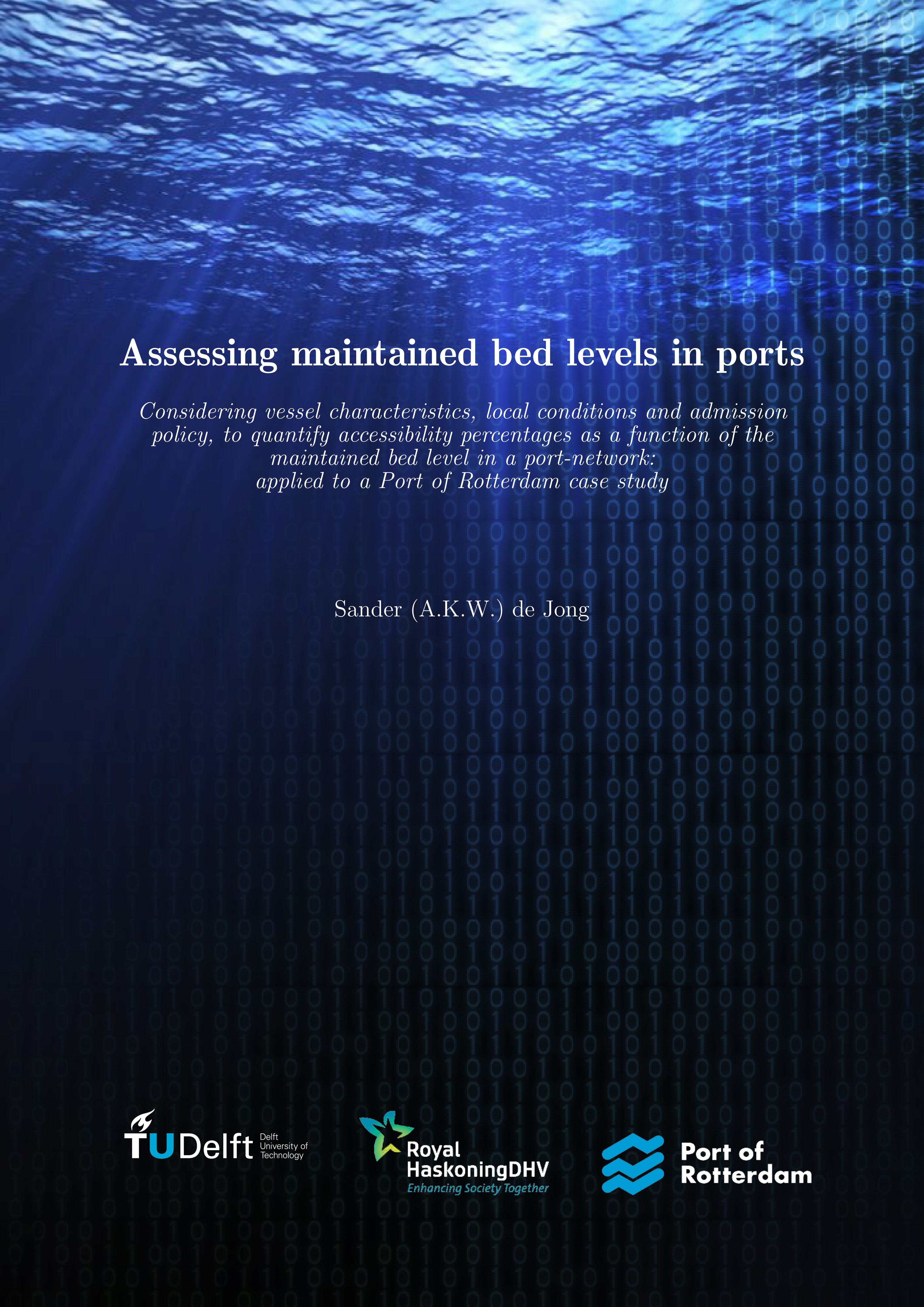

Assessing maintained bed levels in ports

Considering vessel characteristics, local conditions and admission policy, to quantify accessibility percentages as a function of the maintained bed level in a port-network:
applied to a Port of Rotterdam case study

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Enhancing Society Together

Port of Rotterdam

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by

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Preface

This research has been conducted as a part of the master Hydraulic Engineering at the TU Delft. It has been the final effort and trial to earn the title Master of Science in the field of Hydraulic Engineering. It marks the final stage of my master's and the beginning of a professional career. I would like to take this opportunity to sincerely express my gratitude to the people that have provided me with their support and guidance throughout this process.

This research has been performed in collaboration with Royal HaskoningDHV and the Port of Rotterdam. Two leading companies in the maritime sector. The combination of theoretical and practical knowledge from colleagues has provided me with an excellent environment to conduct this research.

First, thank you to my professor and chair of committee Mark van Koningsveld. Thanks to our shared enthusiasm in this research, and especially in modelling, you kept challenging me to take the model to a higher and more generic level. Because of this, I have been able to push my boundaries and I am grateful for that.
To Gosse de Boer, your constant feedback throughout the process was indispensable. If I didn't know where to look anymore, you helped me find the common thread again.
To Pieter Nordbeck, my supervisor at the Port of Rotterdam, you not only guided me with this research, but really introduced me to the world of ports. I am very thankful.
To Joost Lansen and Pieter van Gelder, for their useful feedback and support during this process. Thank you for everything.

And finally, to all the people I have interviewed. Conducting this research was not possible without you. I would especially like to thank Captain Ben van Scherpenzeel - the epitome of the Port of Rotterdam - for the time you regularly took to explain to me how things work in practice. Hopefully, you can forgive me for using maintained bed levels instead of depths. I also want to especially thank Ben Edmondson of Royal HaskoningDHV, for his quick and sharp responses when I got stuck in my code again.

Sander de Jong
Rotterdam, September 2020

Abstract

Research introduction
The accessibility of a port, which is mainly determined by the available water depth, is of economic importance for a port to distinguish itself from other ports. For the vertical design of navigation channels, the goal is to make routes equally accessible and not have bottlenecks; to have an optimal maintenance program and not incur unnecessary costs.
The available water depth is a product of the Maintained Bed Level (MBL) and the local water level. Encountered water levels can vary in time and space, and can be influenced by a tidal window. Determining the required MBL's along a route can therefore be complicated and often provides room for improvement. Moreover, most channels are designed for a certain design vessel draught. In practice, however, the actual draught is often smaller because vessels are not always fully loaded. Also, the vessel that was designed for may no longer call at the port. The aspect of actual vessel draught may therefore lead to a smaller required water depth and affects the required MBL.
Ultimately, the vertical design of channels entails a trade-off between the MBL, vessel draughts and the percentage of accessibility.

Research objective and approach
The objective of this research is to assess the available and required water depths in ports, and to identify opportunities for the vertical design of channels. To reach this objective, a literature study has been carried out. Vertical design approaches, vessel characteristics, local conditions and admission policies are considered. Also, since this topic is strongly related to practice, a relatively large number of interviews were conducted.
In the existing literature, methods do not provide the possibility to assess the trade-off between the facilitated MBL's and related accessibility percentages in a port-network. A more detailed (less conservative) design approach is lacking. Also, assessing the actual draught of vessels for vertical channel design purposes appears relatively new. In this thesis, a traffic data analysis is performed, a new approach to assess the vertical design of channels in a port-network is framed, and a computer model to perform such an assessment is developed. A case study is required to analyse the traffic data and to validate the results of the computer model.
The Port of Rotterdam is a port with a great history; it continuously adapts to cater for increasing traffic volumes and larger vessel sizes. The Port of Rotterdam has observed logistic bottlenecks in trajectories; accessibility percentages can vary along a route. Moreover, it has become unclear how, and for which draughts, some parts of the port have been designed. The accessibility of existing channels is not reviewed. Because of the previously mentioned, the Port of Rotterdam is an interesting case study. Four terminals, with different business-dynamics, handling the largest-draughted vessels in channel sections (normative vessel draughts), are selected.
The results of this study are presented and supported by relevant actors in the port: shipping line, terminal, port authority and pilot.

The proposed vertical design approach
In this study, a new, more detailed vertical design approach has been framed. Ultimately, the vertical design of channels revolves around available and required water depths. Since parameters to determine these depths vary in time and space, a systemic-view is required to design for the same accessibility percentage along a route. In this research, a general method to quantify accessibility percentages as a function of the MBL in a port-network has been framed. By looping over the MBL, corresponding accessibility percentages can be calculated. As a result, it becomes possible to maintain bed levels for neither too little (bottlenecks) nor too much (unnecessary dredging costs) available water depth.

Model development

The MBL model has a general set up; it can be applied to ports all over the world. In the tool, a network of routes can be created. Properties (of vessels and channels), local policies and conditions (data), can be assigned to the network. Subsequently, calculations (such as analysing available and required water depths) can be performed on the entire network. The model calculates available and required water depths along the routes, considering parameters like vessel speeds, local water levels, tidal windows, freshwater allowances, underkeel clearance policies and desired accessibility percentages. It scans for tidal windows and determines the required MBL.

Most important conclusions and recommendations

- The MBL model allows a port authority to be more rational about where to maintain for which bed level. By looping over the MBL's in channels, accessibility percentages can be quantified as a function of the MBL. Bottlenecks and structural over-depths on routes can be identified. Subsequently, accessibility percentages can be aligned over trajectories in a port-network. By removing structural over-depths, dredging costs can be saved. By removing bottlenecks, entire routes can become more accessible with relatively little dredging work.
- From the traffic study, it was concluded that there can be a significant discrepancy between actual and design vessel draughts. For example, only <0.1% of the largest container vessels (16-17m vessel design draught) handled in the *Prinses Amaliahaven* (almost) reach the draught for which channels has been designed (17m). Also, the draught for which channels have been designed in the *Mississippihaven* (22.6m), was last (almost) reached in January 2016. The largest draught that has been reached since May 2016 is 4m below the design draught (18.6m). Based on interviews, the following could be concluded: if shipping lines would better coordinate their expected actual draughts with a terminal for a certain period, a win-win opportunity arises for port authority, terminal and shipping company because dredging costs can be saved.
- The actual use and accessibility of channels in ports should be reviewed on a regular basis. There was observed that channels are not always used (anymore) by the vessels for which they were once designed. This difference can grow due to market demand and port development.
- Due to different perspectives on the required water depth by shipping liner and port authority, the available water depth is not always efficiently utilised. Shipping liners generally apply additional (more conservative) margins for safe navigation. This could be overcome if a port would have an IMO-certificate for standardised best industry practices (for designing channels, acquiring local data and making forecasts). Such a certificate does not exist yet but could help the industry move forward.

It would be expected that something as fundamental as the maintained bed level would be fully thought out in ports. It is compelling that by combining different data-sets (water levels, actual vessel draughts, and currents in case of a tidal window), room for improvement can be found.

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Nomenclature

Acronyms and abbreviations

AIS	Automatic Identification System
ALAT	Approximately Lowest Astronomical Tide
AM	Asset Management
Avanti	Access to Validated Nautical Information
CD	Chart Datum
DHMR	Division Harbor Master of Rotterdam
DTP	Dynamische Tijpoort Viewer
DUKC	Dynamic Underkeel Clearance
FWA	Fresh Water Allowance
HaMIS	Harbour Master Management Information System
HAT	Highest Astronomical Tide
HCC	Harbour Coordination Center
HME	Hydro-Meteo Effects
HW	High Water
IHO	International Hydrographic Organization
IMO	International Maritime Organization
LAT	Lowest Astronomical Tide
LLWS	Low Low Water Spring
LRR	Loodsencorporatie Rotterdam-Rijnmond
LW	Low Water
MBL	Maintained Bed Level
MD	Maintained Depth
MM	Manoeuvrability Margin
MSL	Mean Sea Level
NGD	Nautical Guaranteed Depth
OSR	Operationeel Stromingsmodel Rotterdam
PIANC	Permanent International Association of Navigation Congresses
PoR	Port of Rotterdam
Pronto	Ports Rendezvous Of Nautical and Terminal Operations
Royal HaskoningDHV	RHDHV
RWS	Rijkswaterstaat
Tmax	Maximum static draught of design vessel in salt water
UKC	Underkeel Clearance
ρ	Density

Units of measurement

cm	centimetre
m	metre
km	kilometre
kn	knots
%	percentage
s	seconds
hr	hours

1 Introduction

1.1 Background

Ports have to adapt

Ports are subject to continuous change. In order to maintain a strong market position, they must adapt to technological, socio-economic and environmental developments. Port development is required to accommodate developments such as increasing vessel sizes and traffic volumes. Port authorities have to consider this in the vertical design and maintenance of navigation channels. The carrying capacity of container vessels, for example, has increased with approximately 1200 % since 1968 [Marine Insight, 2019]. The Port of Rotterdam (PoR) is an example of a port that has had to adapt enormously throughout history. The first vessel that sailed through the *Nieuwe Waterweg* was the steamship Richard Young, which had a draught of 3m [Algemeen Handelsblad, 1872]. Recently (almost 150 years later), the *Nieuwe Waterweg* has been deepened to allow vessels with a draught of 15m.

Depth and bed level definitions

Several definitions are used to describe the available water depth in a channel: advertised-, contractual-, controlling-, dredger-atlas-, guaranteed-, nautical-, nominal-, maintained-, proclaimed- and channel- depth. This creates confusion. The internationally nautical accepted term has now become the Maintained Depth (MD). The International Taskforce Port Call Optimization [2020] has defined the MD as follows:

"*The depth at which a channel is kept by human influence, usually by dredging*".

However, this term is also confusing. The depth at a location can change in time (due to tidal variations) and is not a constant that can be maintained. So a certain depth is available for a certain percentage of the time. The available water depth depends on the Maintained Bed Level (MBL) and a local water level. The MBL is a bed level that is strived for in the maintenance program of an authority. So the MD depends on the MBL and a water level that is designed for (corresponding to design accessibility). A more precise definition of the MD would be:

"*The minimum depth an authority strives for to facilitate in a navigation channel (excluding extreme conditions), this is incorporated in the bed level maintenance program*".

For shipping lines, the maintained depth (and related channel accessibility) is of importance. For dredgers, preference is given to refer to the maintained bed level. From a Civil Engineering point of view, it is more logical to refer to a fixed level. Hence, it is preferred to refer to the MBL instead of the MD in this study.

Moreover, the actual bed level is often lower due to a maintenance margin; this is called the 'overdredge'. The actual bed level is determined with soundings. The overdredge is applied to reduce dredging activities and to include a safety margin. The dredged bed level is called the 'channel dredge level'.

Reference levels

A bed level can be described with relation to a reference level. Most countries use Chart Datum (CD), defined as Lowest Astronomical Tide (LAT), as the reference level for sea charts and port areas [PIANC, 2014]. The LAT has internationally become the normative low-water level in tidal port-areas and sea access channels since 2007 [Rijkswaterstaat, 2020]. The International Hydrographic Organization (IHO) decided to adopt the LAT as the international marine chart datum. Countries often also have their own local CD. In the Port of Rotterdam estuary, for example, river discharge also influences the water level. Therefore, an Approximately LAT (ALAT) is referred to in the PoR. Extreme low water levels (lower than (A)LAT) may occur due to wind and air pressure. These are called Hydro-Meteo Effects (HME). HME is a statistical value based on local historical data. Based on the LAT and HME, the extreme low water level can be determined, for which ports can design to achieve the desired accessibility percentage. In addition, bed levels are often given with respect to the *Nieuw Amsterdams Pijl* (NAP) reference level in the Netherlands. A NAP height of 0 m was approximately equal to the Mean Sea Level (MSL) of the North Sea. In general, a tidal wave dampens out in an estuary. That is why the difference between the ALAT and NAP decreases towards the city centre of Rotterdam. Moreover, NAP is a fixed level and is not calibrated with sea-level rise. So due to sea-level rise, the MSL has become higher than NAP.

Figure 1.1 provides an overview of the previously mentioned topics.

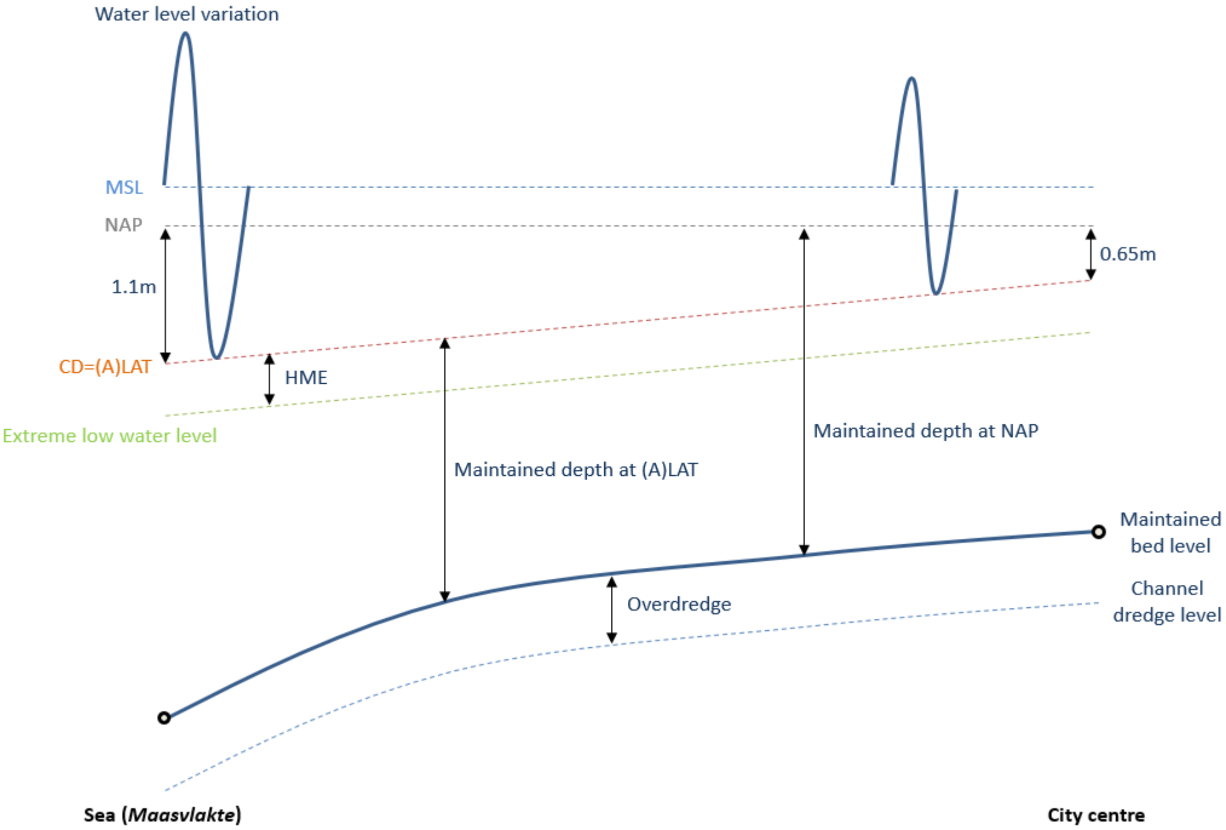


Figure 1.1: Overview of reference water levels, maintained depth and bed level: PoR example

Vessel related factors

Navigation channels are designed for a certain draught. This draught is statically measured in seawater. Hence, it is called static draught (by PIANC [2014]). In this study, 'draught' refers to the static draught. A vessel has less buoyancy and therefore a larger draught in freshwater than in saltwater. This difference is called the Fresh Water Allowance (FWA). Moreover, when a vessel is fully loaded, the vessel's design draught is reached. Since vessels are not always fully loaded, there is often a difference between a vessel's actual draught and design draught. If a channel is designed for a certain vessel design draught, the available water depth is not (always) fully used. In addition, the distance available under a vessel's keel, the Underkeel Clearance (UKC), plays an important role in MBL calculations. The UKC influences the manoeuvrability of a vessel and is closely related to safe navigation since it affects the risk of hitting the bed. In Chapter 2, Figure 2.1, a build-up of UKC factors is presented as proposed by PIANC [2014]. In this study, 'UKC' refers to the minimum required gross UKC. To achieve sufficient UKC, the draught of a vessel can be restricted, sailing speed can be reduced to reduce sinkage (squat), a vessel can be restricted to a high water period of the tide, and the MBL can be deepened through dredging.

An overview of the previously mentioned is presented in Figure 1.2.

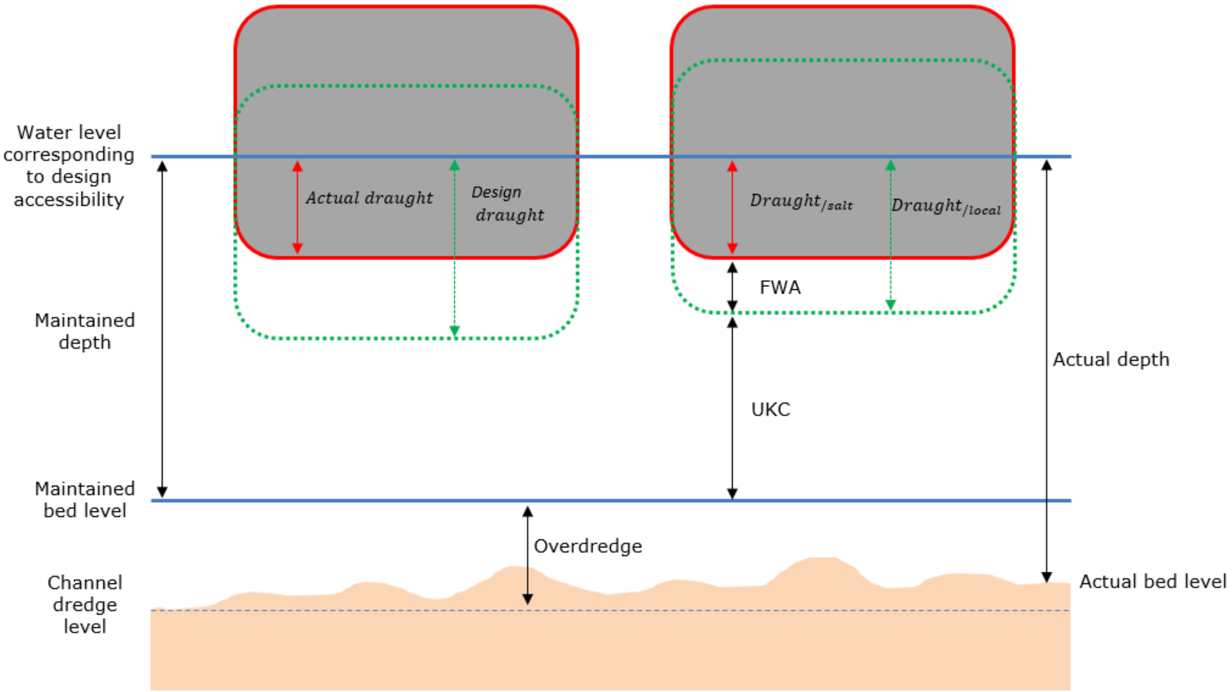


Figure 1.2: Important draught, depth and bed level definitions

Vertical design of channels and accessibility (tidal windows)
The vertical design of channels is a trade-off between accessibility and dredging costs. Maintenance dredging is required for many ports to keep channels accessible. This is a large recurring expense and can have a substantial impact on the environment. To reduce dredging activities, a port is often designed to handle vessels with larger draughts at terminals closer to sea for larger natural water depths. Also, the accessibility of the largest vessels is often restricted to a limited (high water) period of the tide. This is called a vertical tidal window and makes vessels tide-bound. By making a vessel waiting for high(er) water outside a port, a shallower MBL suffices. At the berth, there is often a pocket so the vessel can be moored without touching the bed at low water. Sometimes even 'over-the-tide-operations' are in place; a vessel needs to be (partly) unloaded before the water level becomes too low. From an economic point of view, a restriction on a vessel's draught or accessibility is not desirable for a port, as it undermines the accessibility and hence international reputation of the port. So a port authority has to make a trade-off between dredging costs and accessibility to decide what MBL's to facilitate.
Next to a vertical tidal window, an operational horizontal tidal window may also be applied for certain port basins. This tidal window is related to the currents in a channel to ensure safe manoeuvrability of a vessel. A port provides accessibility as a percentage of tidal cycles for tide-bound vessels and as a percentage of time for non-tide-bound vessels.

An overview of tide-related accessibility limitations is presented in Figure 1.3.

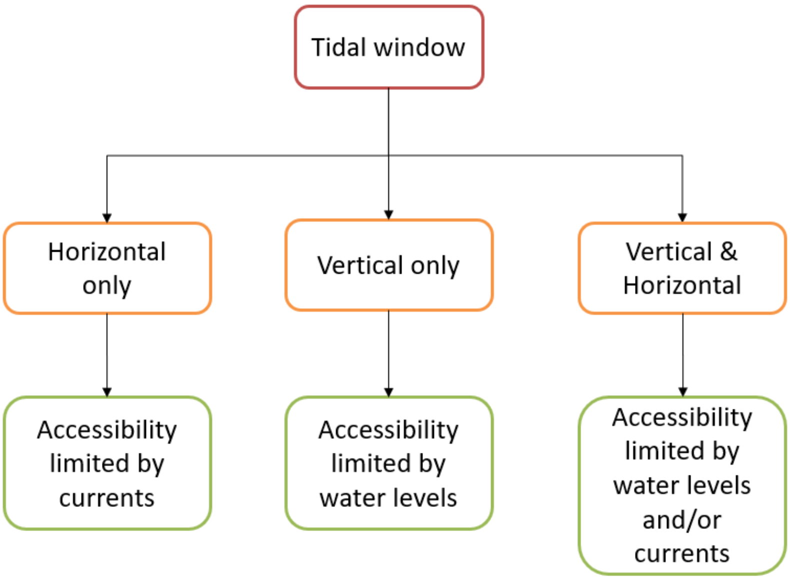


Figure 1.3: Types of tidal windows

In practice, accessibility is also depended on the availability of nautical service providers (tugs and pilots) and channel traffic planning. These considerations are beyond the scope of this study. There is assumed that vessels can enter the port through safe windows.

1.2 Problem statement

Vertical design approach
PIANC [2014]'s design guidelines have broad international support and can be considered as a generally accepted approach. These guidelines are designed to facilitate safe navigation and can be used anywhere. Because they are so general, the results are often conservative and can vary widely [Interviews Royal HaskoningDHV [2019-2020], Onrust [2018]].
ROM is the standard system for channel design in Spain, and it becomes more and more prevalent, especially in South America and Caribbean nations [Puertos del Estado (España), 2007]. For the vertical design of a channel, the results of the PIANC guidelines and ROM standards are almost the same [Jianghao and Degong, 2018]. The Overseas Coastal Area Development Institute of Japan [2002], Thoressen [2014] and Ligteringen and Velsink [2014] also provide information about the vertical design of channels, but its technical standards are in less detail (fewer factors are considered) compared to PIANC's guidelines. The U.S. Army Corps of Engineers [2006] determines an optimum economic channel based on annual costs and benefits, but no further calculation methods are proposed.
Furthermore, multiple studies have been performed on the accessibility of a port approach channel (Savenije [1995], Savenije [1998], Briggs et al. [2003], and Quy et al. [2008]). In these studies, probabilistic calculations on the tide and wave impact are performed to assess the probability of vessel grounding in a port approach channel. Such studies have not been carried out for channels in a port. This is probably because the wave impact is often negligible in a port. Moreover, Thiers and Janssens [1998] have created a port simulation model, in which the depth is an input variable, but the focus of the study is on traffic forecasts and traffic bottlenecks. No recommendations are made concerning the vertical design of channels.
A more detailed (less conservative) vertical design approach for channels in a port is lacking in the existing literature. Current methods do not provide the possibility to analyse the trade-off between the facilitated MBL's and related accessibility percentages in a port-network.

Ultimately, the vertical design of channels revolves around available and required water depths. To not incur unnecessary maintenance costs, there should not be a large gap between the available and required water depth (for most of the time). A larger available water depth than required can be considered as conservativeness. A smaller available water depth than required reduces the accessibility of a channel. The available water depth can vary in time and space. The required water depth varies only in space. It is based on a draught for which has been designed, a freshwater allowance and local UKC policy. The concept of available and required water depth is depicted in Figure 1.4.

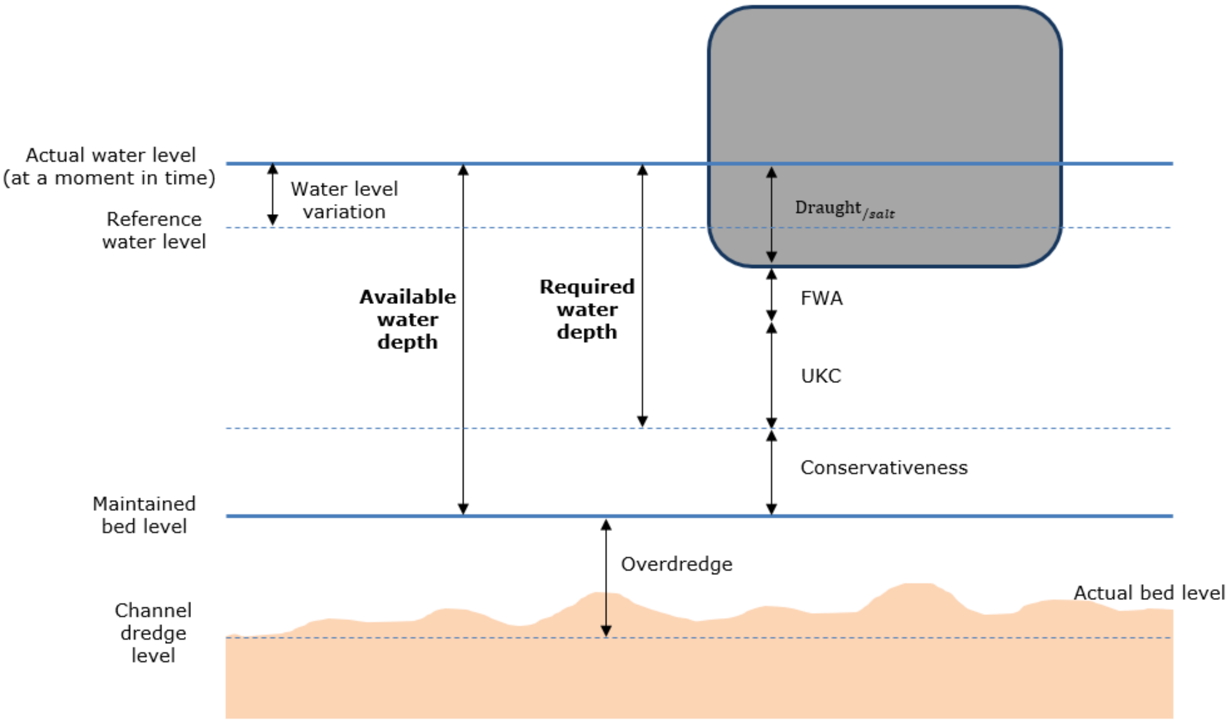


Figure 1.4: Available and required water depth (at a moment in time)

A distribution of available water depths could be made with historical local water levels (data). However, if vessels are tide-bound, there is also a relation between a tidal window and the encountered water levels on a route. Moreover, vessels' speeds vary over a route and influence the encountered water levels. Overall, determining the required MBL can be complicated; the following reasons are identified:

- Water levels can vary in time and space.
- Tidal windows influence encountered water levels.
- Vessel speeds, which vary along a route, influence encountered water levels.
- Local parameters change along a route (draught for which channels have been designed, UKC and FWA).

Parameters to determine the available and required depths vary in time and space. To design for the same accessibility percentage along a route, a systemic-view is required. A computer model would be required to study the relationship between accessibility percentages and the MBL in a port-network. Such a model could be used for:

- Quantify accessibility percentages of channels as a function of the MBL.
- Analyse the MBL and corresponding accessibility percentages of existing channels.

- Building new infrastructure.
- Software to automate port processes (automatic calculation of safe tidal windows).

Actual & design vessel draught
Channels have been designed for a certain vessel draught. Since vessels are not always fully loaded, there is often a difference between a vessel's actual draught and the draught for which have been designed. The available water depth is, therefore, not (always) fully used. Assessing the actual draught of vessels for vertical channel design purposes appears relatively new. The sources Google Scholar, Scopus, ASCE library, research gate and the TU Delft repository have been consulted. The following search terms were used, but did not yield any results in relation to this study: actual-, announced-, design-, traffic data-, vessel/ship draught port.
A distribution of actual vessel draughts could provide insight into how often the draught for which a channel has been designed is reached. If there is a significant discrepancy, MBL's may be designed more efficiently.

Underkeel Clearance policy
The UKC has a great influence on the required water depth and hence vertical design of a channel. Unfortunately, there is no international agreement on how the UKC in a port (section) has to be determined [Interviews Port of Rotterdam [2019-2020], Interviews Ship liner & Terminal [2019-2020]]. Interviews with Maersk Line and the PoR authority revealed that shipping lines and port authorities can have a different perspective on UKC factors to consider and hence policy. The port authority's UKC policy is an imposed minimum UKC, but shipping lines may decide to sail with a safer margin because they prefer their own for safe navigation. A larger UKC (for safer navigation) is achieved at the expense of cargo. This leads to sub-optimal usage of available water depth.

Summarising the identified knowledge gaps:

- A vertical design approach, with a systemic-view, in which accessibility percentages can be quantified as a function of the MBL in a port-network, is lacking in the existing literature.
- It is unknown to what extent available water depths are utilised. Assessing the actual draught of vessels for vertical channel design purposes appears relatively new. There might be a discrepancy between draughts for which channels have been designed and actual vessel draughts.
- There is no international agreement on UKC build-up and factors to consider. A different perspective on UKC policy by port authority and shipping line leads to inefficient usage of the available water depths. There is not yet a solution to overcome this problem.

Observed challenges Port of Rotterdam

The PoR would be an interesting case study. The MBL's in the PoR have evolved. This process is still ongoing due to port development and increasing vessel sizes. At the PoR, the accessibility of existing channels is not reviewed. Hence, the PoR had raised the question whether MBL's are still efficiently designed as such. The PoR has had an analysis carried out in 2018 by *Charta Software* to analyse the customer journey trajectory of a tide-bound outbound tanker from the Euro Tank Terminal. From this research was concluded that certain sections in the port form a bottleneck in the journey of an outbound tanker (Charta Software B.V. [2018]). This may also apply to other routes in the port. More bottlenecks, or over-designed sections, may be identified. Moreover, it is noticed that many MBL's in the PoR equal 65cm behind the comma. In the past, the *Rottepeil* was used as the reference level when designing the depth of a channel [Interviews

Port of Rotterdam, 2019-2020]. This is the normative low water level in the city centre of Rotterdam, which equals -0.65m NAP. This is also depicted in Figure 1.1. When designing for other sections than the city centre, it does not make sense to use the *Rottepeil* as a reference level. The normative low water level varies in space. Even the MBL's of channels in the *Maasvlakte 2*, which was designed in 2006, have this 65cm behind the comma. It seems as if they are based on the *Rottepeil*. The MBL of the Yangtzekanaal, for example, equals NAP - 19.65m. The *Maasvlakte 2* is approximately 40km from the city centre. A normative low water level of -1.10m NAP should have been applied. So it is unclear how these MBL's have been determined and how sufficient they are.
Regarding the PoR's UKC policy, basic rules are applied. They are based on pilot experiences. There might be room for improvement in this policy or in the support base of it.

1.3 Research objective

This research sets out to find opportunities to make better usage of the available water depths in ports. This is done by studying MBL's, UKC policy and analysing traffic (draught) data. Moreover, the research sets out to frame a general method and design a general computer model to assess MBL's in a port-network. There is not yet a design method that analyses available and required water depths in a port-network. Especially the relationship between tidal windows, local water levels and vessel speeds along a route are complex because they vary in time and space. This research aims to compose a general model in which a network of routes can be created, and where required and available water depths for sea-going vessels to or from a berth can be analysed. By computing the accessibility percentages for parts of routes for a range of MBL's, it can become possible to make every part of the route equally accessible. The user can select the desired accessibility percentage. Overall, this model makes it possible to analyse multiple routes, future scenario's and translate changes in the port directly into the vertical design.

The objective of this research can be summarised with the following research question:

> *"How can available water depths in a port-network be used more efficiently, considering maintained bed levels, underkeel clearance policies and actual vessel draughts, for a Port of Rotterdam case study?"*

Four sub-research questions are defined to answer this main question and reach the research objective. The following should be investigated:

- How are maintained bed levels determined, and what are the opportunities for improvement?
- For a location, how is accessibility determined?
- How can accessibility as a function of the maintained bed level be assessed in a port-network?
    (a) What approach is required?
    (b) How can this be modelled?
- To what extent can a statement be made, based on traffic data, on how often the available water depth is used?
- What observations can be made for the Port of Rotterdam (case study)?

1.4 Research approach

Literature study & interviews

Port accessibility is a subject strongly directly related to practice. Important parties are port clients, nautical advisors and the harbour coordination center. To represent the interests of all these parties involved and to understand the dynamics surrounding this topic, a relatively large number of interviews had to be conducted (see Appendix A).

A literature study has been carried out to gain a deeper theoretical understanding of the area of interest. From this, it becomes more clear which subjects, parameters and elements are related to the vertical design of channels. The literature review starts out in general, discussing mainly PIANC guidelines. Subsequently, existing and ongoing developments in this field of research are discussed. Next, the Port of Rotterdam's design standards and policies are analysed to identify room for improvement. Based on the knowledge gained, a new vertical design method is proposed.

Model development

The developed model was written in the Python programming language. Jupyter Notebook, from the Anaconda Navigator application, was used as the graphical user interface to write and run the code. The model and related data are available at the GitHub of the TU Delft Hydraulic Engineering department.

The MBL model has a general set up; it can be applied to ports all over the world. In the tool, a network of routes can be created by using general latitude and longitude coordinates. These locations are projected in space with the 'pyproj' Python-module. The 'Shapely' - module is subsequently used to link these sections and to create a path. Next, the Python NetworkX-package is used to convert the paths to a NetworkX graph object. This package is designed to research the structure and dynamics of computational networks [Hagberg et al., 2008]. Properties (of vessels and channels), local policies and conditions (data), can be assigned to the network. With the Dijkstra's algorithm from the NetworkX package, distances and durations within the network can be calculated (geodetic calculations). Moreover, to handle dates and times in a general way, the 'DateTime' Python-module has been used. Dates and times are converted to a timestamp (number) and stored in a database. A Unix timestamp is the number of seconds between a particular date and January 1, 1970, at UTC.

With methods (functions), the same calculations (such as analysing available and required water depths) can be performed on the entire network. The tool scans for tidal windows and determines whether to design for tide-bound vessels or not. The tool makes it possible to translate changes (to which a port is constantly subject), directly into the vertical design. This is even true for parameters such as vessel speeds, desired accessibility percentages and tidal windows, which are currently not directly in design approaches.

Case studies

To reach the objective of this research and test the tool, case studies with different business dynamics in the PoR were selected. Required local conditions data (water levels and currents) to set-up the model were obtained from NAIADE - the PoR 'weather & tide' desktop. Traffic data were retrieved from the PoR harbour management system HaMIS. Based on AIS signals, the PoR has been storing moments vessels passing a certain location in the port. This data was used to calculate vessel speeds along various routes in the port.

Finally, the findings of this research are presented to relevant actors (port authority, terminals, shipping lines, pilots) to discuss the results.

1.5 Research scope

This section sets out to specify the scope of this research. The conducted interviews (Appendix A) helped to provide the (historical) context and a practical point of view regarding the discussed topics. This helped to obtain a realistic scope and to give findings of this research the potential to be implemented. A general approach is applied, with the intended purpose to make this research applicable to multiple ports and routes. The model is tested on Port of Rotterdam case studies.

There is assumed that vessels can enter the port through safe windows. The availability of nautical service providers (tugs and pilots) and channel traffic planning is beyond the scope of this study.

It can be argued that overdredge should be a part of the conservativeness (Figure 1.4). However, this has to do with practical dredging policy and is not part of the scope. Depths and bed levels are considered from a theoretical point of view in this study. From an operational point of view, actual depths and actual bed levels would have to be considered.

The focus in the model lies on fairways, basins and berths, not on the port approach channel. In the approach channel in the PoR, a Dynamic UKC (DUKC) policy is in effect. This policy is more based on wave spectra, wind speeds and stability of vessels. This is a different study in which more probabilistic design considerations are applied. This is only briefly discussed (in Section 2.1.4). Also, only seaport transport is considered in this research, because these are the largest-draughted vessels that determine the required MBL in the channels. The considered routes are from sea to berth (inbound) or vice versa (outbound).

Dynamic factors such as squat and heel are included in the UKC. More information on this topic is provided in Section 2.1.3. Also, existing UKC studies are used, a hydro-dynamical study is not performed. Likewise, the impacts of adjusting the bed level are considered, a full economic study is not part of that. Also, the height of bridges (related to air-draught) and water level depression due to vessels passing each other have not been included in this research and computer model. As for the freshwater allowance, water densities in channels vary all the time due to tides and winds. A maximum safe allowance is used (worst case scenario); this is not investigated further.

Furthermore, the vertical design (MBL) of channels is assessed in this research. The horizontal design (top view shape) of channels are currently being optimised by the PoR based on Automatic Identification System (AIS) vessel tracks. The progress is appointed in Section 2.2.2 but is not investigated any further.

This research can provide certain recommendations for the MBL, but these depths are contractually fixed. A deep dive into these contracts is not part of the scope of this research. The opinions of insurers regarding the amendment of the UKC policy have also not been included.

Moreover, the expected effects of climate change on local conditions have not been studied. Water levels and currents may be different in the future. At last, the results of this study were not influenced by COVID-19; traffic data was obtained before this crisis.

1.6 Thesis outline

Chapter 2 sets out to provide the required technical background to identify room for improvement. Topics related to MBL and accessibility are studied to determine a new design approach. General theoretical points of view are considered. This is supplemented with more practical points of view (from especially the PoR) and ongoing developments in this research field. By doing so, the first two sub-research questions can be answered.
In Chapter 3, a new vertical design approach is framed, and the required model is developed. This model is developed to be able to quantify accessibility percentages as a function of the maintained bed level in a port-network. The modelling concept, structure, input and output are described. Also, an internal validation of the model is performed. At the end of this chapter, the third sub-research question can be answered.
Case studies are performed in Chapter 4; traffic data are analysed and further applications of the MBL model are presented. This chapter addresses the final two sub-research question: observing traffic data and making recommendations for the PoR (based on the model). The MBL's and

accessibility of existing channels are assessed. Also, alternative vessel draughts (model input) and the related effects on the vertical design of channels are assessed.

Chapter 5 discusses the application and output of the model. Finally, the main research question is addressed in Chapter 6; the conclusions of this study are described, and recommendations for further research are made.

2 Technical background

Chapter outline

This chapter sets out to provide the reader with the required technical background. It is a result of the literature study and also considers more practical points of view. Topics related to bed levels and depth are discussed. This chapter addresses the following sub-research questions:

- How are maintained bed levels determined, and what are the opportunities for improvement?
- For a location, how is accessibility determined?

In Section 2.1 general points of view regarding channel depth, water levels, bed levels, draught and UKC are discussed. In Section 2.2, ongoing developments regarding this topic are discussed. Consequently, in Section 2.3, more in-depth Port of Rotterdam policies are described. This includes a more practical point of view towards accessibility, dredging and port income. Next, in Section 2.4, the general impact of adjusting the MBL is discussed. Finally, this chapter will conclude in Section 2.5 with answering the above questions.

2.1 General: Water depth

Permanent International Association of Navigation Congresses (PIANC) provides expert guidance, recommendations and technical advice to governments and private sectors in the design, development and maintenance of ports and channels all over the world. It is a non-political and non-profit organisation that connects leading international experts on technical, economical and environmental issues regarding waterborne transport infrastructure. PIANC guidelines have broad international support and can be considered as a generally accepted approach.

Furthermore, the *Ports Designers Handbook* [Thoressen, 2014] and *Ports and Terminals* [Ligteringen and Velsink, 2014], which are in line with PIANC guidelines, will be used to substantiate general approaches.

Figure 2.1 presents factors influencing channel depth according to PIANC. These factors and their influences are discussed in this section. Thoressen [2014] and Ligteringen and Velsink [2014] have presented comparable but less detailed figures. Firstly, the water level factors are discussed, subsequently the bed level factors and finally, the vessel related factors (draught and UKC).

2.1.1 Water levels

The following factors are relevant to the channel depth with respect to the water level:

- Reference water level:

  A reference level must be defined to relate all factors to. Most countries use Chart Datum (CD), defined as Lowest Astronomical Tide (LAT), as the reference level for sea charts and port areas [PIANC, 2014]. At LAT, CD equals zero. The LAT has internationally become the reference water level in tidal port-areas and sea access channels since 2007 [Rijkswaterstaat, 2020]. LAT has replaced Low Low Water Spring (LLWS) [Rijkswaterstaat, 2020]. LAT is a water level based on the minimum of the predicted low-waters due to the influence of the sun and moon in the current hydrological state. In other words: it is the lowest predictable water level, so all astronomical predicted water levels are higher than LAT. LAT values are subject to change due to sea level rise and have to be calibrated once in a while. Moreover, in the Netherlands bed, levels are often given with respect to *Nieuw Amsterdams Pijl* (NAP). A NAP height of 0 m was approximately equal to the Mean Sea Level (MSL)

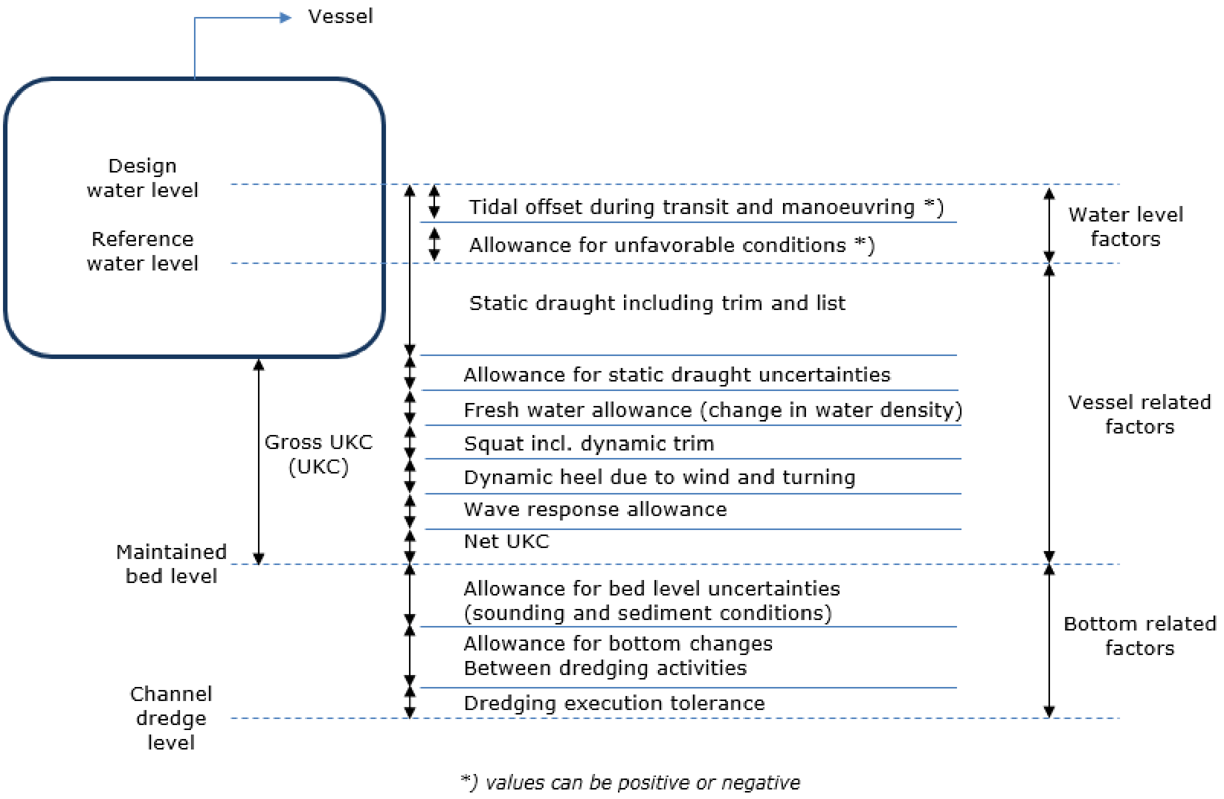


Figure 2.1: Channel depth factors (based on PIANC [2014])

of the North Sea. So it is location specific and can't be used internationally. NAP is a geodetic level and isn't calibrated with sea level rise. Due to sea level rise, MSL has become higher than NAP.
Moreover, in Japan, the chart datum level is obtained by subtracting the sum of the amplitudes of the four principal tidal constituents (M2, S2, K1 and O1) from the mean sea level [The Overseas Coastal Area Development Institute of Japan, 2002]. The result is a NLLWL (Near Lowest Water Level), which is different from the LAT.

- Design water level:

  A design water level is defined by taking tidal and meteorological effects into account. The design water level also depends on the type of design. For example, for the design of a breakwater, the Highest Astronomical Tide (HAT) is often used to consider amongst other over-topping effects. For the design of a navigation channel, LAT is often used to design for a high accessibility percentage.

- Tidal and meteorological effects:

  Astronomical tides and meteorological effects influence the water level. Meteorological effects include wind set-up and local atmospheric pressure variations. A pressure drop increases the water level. Furthermore, tides are the rise and fall of the seawater level induced by the rotation of the earth and the gravitational forces exerted by the sun and moon. They vary in time and space. Due to these tides, tidal windows may be applied. Dredging costs can be reduced by allowing accessibility only during a relatively high water level. This tidal window refers to the vertical tide. In addition, a horizontal tidal window may be applied. This is related to currents; currents include tidal streams and wind-induced currents. In some (parts of) ports, tidal streams are too strong at a certain period in the tidal cycle to allow some vessels to navigate safely. Especially to manoeuvre safely into a port-basin.

This can result in an accessibility restriction. Therefore, large-draughted vessels often enter a port-basin around high water slack. Water levels are high and tidal streams are low.

It is important to distinguish in- and outbound vessels. Inbound vessels can enter the port on a high or rising tide. If they can sail approximately as fast as the propagation speed of the tidal wave, they can remain on that high water level. Outbound vessels have to sail against the tide and therefore experience different water levels. This difference is depicted in Figure 2.2.

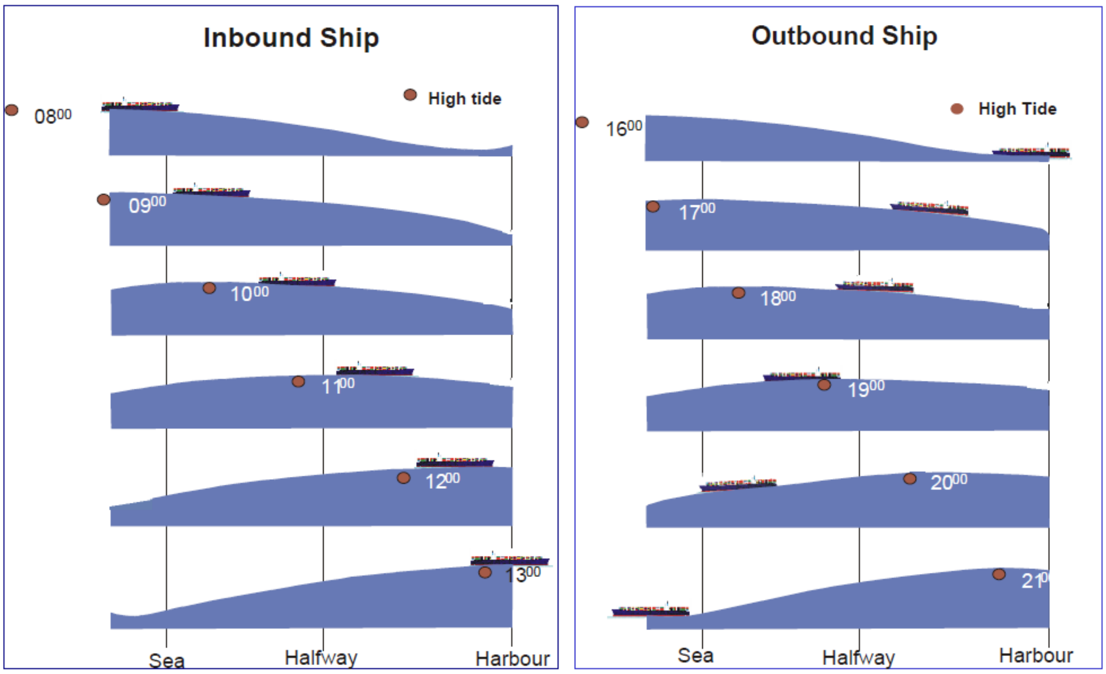


Figure 2.2: Example difference between inbound and outbound vessels with relation to tides [PIANC, 2014]

Due to tidal variations, vessel speed is an important aspect of the design process. It influences the water levels a vessel encounters in relation to a tidal window. Moreover, manoeuvrability is negatively affected if the speed is too slow. If it is too high, problems related to squat, riverbank erosion and reflection are increased.

If applicable, seasonal variations in river discharge due to wet or dry seasons could be considered in the design. Finally, the effect of sea level rise is not included by PIANC, but could be considered.

2.1.2 Bed level factors

There has to be a safe distance between the deepest point of a vessel and the channel bed. An authority strives for a certain bed level in its maintenance program, the MBL. To include a safety margin and reduce dredging activities, a lower level is dredged than the MBL. This is called the 'channel dredge level'. Three bed related factors that lead to this dredged level are discussed in this section. Special considerations in case of a muddy bed are described in Section 2.2.1.

- Allowance for bed level uncertainties:

  There is an uncertainty in the measured actual bed level due to the degree of accuracy of the bathymetric survey data. There is always a measurement tolerance that has to be considered when using sensors. PIANC recommends a minimum allowance for bed level uncertainty of 0.1m.

- Allowance for bed changes between dredging activities:

  Between dredging activities, sedimentation could occur. To reduce dredging activities and increase the time between dredging cycles, the dredged bed level is deeper than the required MBL. This allowance is therefore also called the 'Advance Maintenance' allowance due to the over-dredging. The value of the allowance is very site-specific and should be based on local experience. PIANC recommends a minimum value of 0.2m or 1% of the channel's bed level (with relation to a reference level) for the allowance of bed changes between dredging.

- Dredging execution tolerance:

  The bed is not perfectly flat after dredging. Hence, to ensure the MBL at all places after dredging, the bed level is over-dredged. So this dredging execution tolerance is because of over-dredging. According to PIANC, 0.2 to 0.5m is a common dredging execution tolerance, depending on the type of bed and dredger.

2.1.3 Vessel related factors

Static draught

As mentioned before, with 'draught' is referred to the static draught. To reduce uncertainties, this is preferably measured in salt water, when the vessel is not sailing and is not subject to wave influences or other vessel motions. If a port basin is located in fresher water, there is often referred to a 'local draught' (at berth) for outbound vessels. This includes a fresh water allowance. For inbound vessels is referred to a salt water draught. It is essential to distinguish three types of draughts for the vertical design of a channel:

- A vessel's design draught: reached when it is fully loaded.
- A vessel's actual draught: the draught a vessel actually has loaded to. This may be smaller than the vessel's design draught.
- A draught for which a channel has been designed: this draught can also differ from a vessel's design and actual draught.

The maximum draught can vary in time due to fuel consumption and ballast adjustments, for example. If a vessel doesn't have a constant draught over its length, the maximum should be used (which is often at the bow or stern). Please note: the draught for which a channel has been designed can be smaller than the maximum draught of the design vessel. This means there isn't enough depth available for the design vessel to arrive fully loaded (with a maximum draught) at the berth.

In addition, a vessel has a scantling draught. This is the maximum draught a vessel can load to and still safely handle the stresses. In other words, it is the maximum draught a vessel is built for in terms of strength [Wartsila Encyclopedia, 2020]. The air draught of a vessel is the maximum distance from the water level to the highest point of the vessel.

Furthermore, a practical load line is still used worldwide. This line is also known as the Plimsoll mark. It is a mark located on a vessel's hull that indicates the draught a vessel can safely load to. The mark depends on vessel's dimensions, type of cargo and seasonal zones. Water temperatures affect a vessel's draught. Warm water is less dense than cold water, providing less buoyancy. Hence, the maximum draught is often related to 'summer draught'. When loading, a captain uses the seasonal zone's Plimsoll line of its current location. Figure 2.3 presents an example of a Plimsoll mark on a vessel's hull.

Figure 2.3: Plimsoll mark on a floating vessel's hull [Oceanservice, 2020]

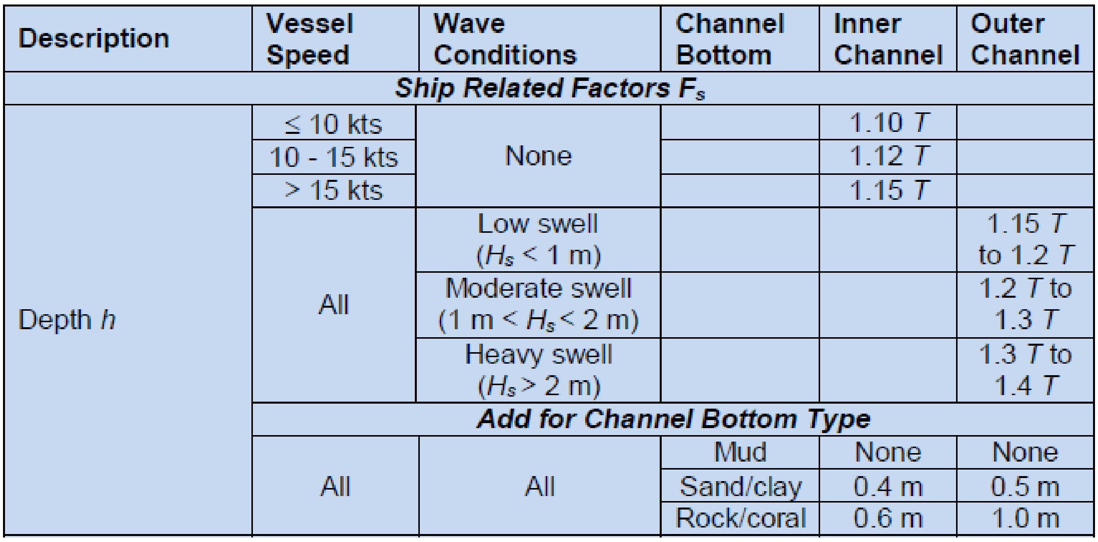
TF = Tropical Fresh Water
T = Tropical
F = Fresh Water
S = Summer
W = Winter
WNA = Winter North Atlantic
AB = Indicates the registration authority (American Bureau of Shipping in this example).
= In addition, the line indicates whether or not the cargo is loaded evenly

Underkeel Clearance

PIANC provides a build-up of factors to consider when determining an UKC and discusses rough design approaches. However, the results vary widely and are conservative (Onrust [2018], Interviews Royal HaskoningDHV [2019-2020]). It is highly dependent on location and situation. A concept design approach by PIANC that combines squat, dynamic heel and wave response allowance into one factor is presented in Figure 2.4. Previously mentioned literature, and HelCom [2013], do not provide better tools either.
Determining an appropriate UKC based on theory is difficult. Based on the previously mentioned and interviews with experts [Interviews Royal HaskoningDHV, 2019-2020], it is concluded that UKC policies are understandably often based on experience and iteration.

The gross-UKC consists of six factors. In addition, a manoeuvrability margin (a minimum UKC) is discussed.

- Gross UKC:
  - Allowance for static draught uncertainties:
    There is always uncertainty in the exact vessel's draught. It is usually measured at the port of departure, which can have a different water density than the port of arrival. In addition, there can be an inaccuracy in the measurement due to wave conditions. Waves can also make it difficult to accurately read draught markings on the vessel's hull. A static inclination as a result of unbalanced load (i.e. list) is another cause of uncertainty. Therefore, a safe allowance is made.



Description	**Vessel Speed**	**Wave Conditions**	**Channel Bottom**	**Inner Channel**	**Outer Channel**
Ship Related Factors F_s					
Depth h	≤ 10 kts	None		1.10 T	
	10 - 15 kts			1.12 T	
	> 15 kts			1.15 T	
	All	Low swell (H_s < 1 m)			1.15 T to 1.2 T
		Moderate swell (1 m < H_s < 2 m)			1.2 T to 1.3 T
		Heavy swell (H_s > 2 m)			1.3 T to 1.4 T
	Add for Channel Bottom Type				
	All	All	Mud	None	None
			Sand/clay	0.4 m	0.5 m
			Rock/coral	0.6 m	1.0 m

Figure 2.4: Concept design: all vessel related factors into one factor [PIANC, 2014]

- Change in water density:

  Differences in specific mass between fresh and salt water lead to differences in the draught. The draught of a vessel increases (sinkage) when it sails from salt water into fresh water, because of the lower density. The draught increases almost proportionality to the density difference, which is 2 to 3 % in fresh water compared to sea water.

- Vessel squat, including dynamic trim:

  Squat is a hydrodynamic phenomenon that leads to sinkage due to the vessel's speed. A water level depression is induced by a relative velocity between the vessel and the surrounding water (the Bernoulli effect) in which the vessel sinks. This effect is significantly increased in shallow water and when sailing close to a bank. In addition, a moment about the transverse axis is induced; this is called trim. It can result in different draughts at the bow and stern. The maximum squat often occurs at the bow, but can also occur at the stern (in narrow channels and for high-speed vessels, such as ferries and container vessels) [PIANC, 2014]. The differences between sinkage, trim and heel are clarified in Figure 2.5. So squat leads to a decrease in UKC due to sinkage and trim. This effect is approximately proportional to the square of the vessel's speed. The squat is decreasing as vessel's speed decrease as they get closer to the berth. It has become more of a concern due to increased vessel sizes, which are sailing with higher speeds and smaller UKC. PIANC [2014] provides seven empirical squat formulas.

- Dynamic heel:

  When a vessel heels to a side, the vessel's draught increases. Heeling is caused by the turning of a vessel and non-oscillating wind forces and currents. Especially container vessels are sensitive to this effect because of their high surface-area and resulting wind forces. Heel angles of 3 degrees have been observed [Ligteringen and Velsink, 2014]. Moreover, the magnitude depends on the vessel's speed, turning rate, distribution of weight aboard and tugboat line forces, for example. Wave-induced oscillations are called roll.

- Wave response allowance:

  Waves can induce vessel motion. Figure 2.6 illustrates the six degrees of freedom. Heave, roll and pitch are the vertical components that affect the vertical design of the channel. If a vessel sails in a narrow channel where large waves are present, this is

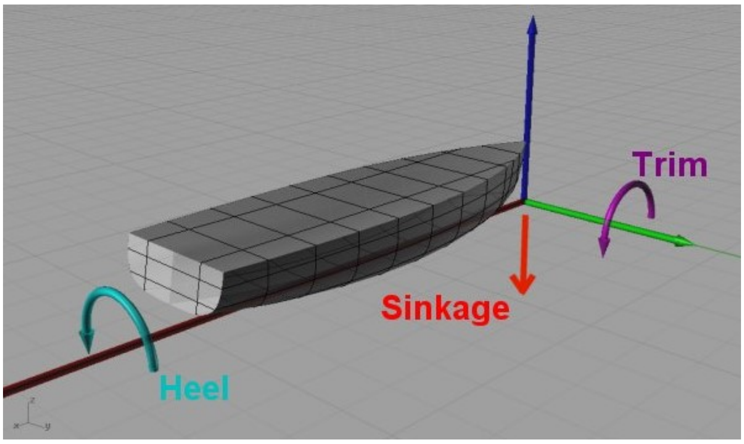


Figure 2.5: Squat (trim and sinkage) and heel [Orca3D, 2017]

potentially the largest vessel factor. As a vessel moves more inland, the influence of waves usually decreases due to sheltering. Four methods to calculate the wave-induced motion are described by PIANC [2014].

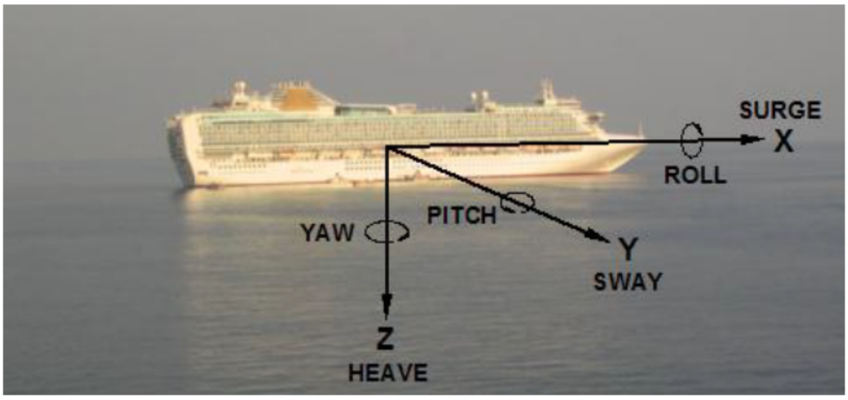


Figure 2.6: Six degrees of freedom: wave-induced vessel motion [PIANC, 2014]

  - Net UKC:
    The Net UKC can be defined as the minimum margin between the vessel's keel and nominal channel bed level. Hence, it is a final safety margin after subtracting the previously mentioned vessel factors from the nominal channel bed level. It should be based on the type of bed (larger consequences for hitting a rocky bed than a muddy bed), type of vessel (size and commodity) and environmental consequences. PIANC [2014] recommends a value between 0.5 and 1.0 m.

- Manoeuvrability margin (MM)

  A manoeuvrability margin can be considered as a minimum Gross UKC requirement to make sure a vessel has adequate manoeuvrability. This means the pilot is able to manoeuvre without the assistance of tug boats. It is an independent check. In the calculation of the MM, only motions that affect the lowest position of the vessel are considered. Wave-induced vertical motions (heave, pitch, roll) don't have a significant effect on the manoeuvrability [PIANC, 2014]. Hence according to PIANC [2014], MM equals: available water depth - draught - squat - heel. For most vessels (sizes and types) and channels; 5% of a vessel's draught, with a minimum of 0.6m provides adequate MM. With tug assistance, a MM of 0.5m is commonly used.

2.1.4 Probabilistic design considerations

In channels exposed to wave action, wave-induced motion is the largest factor influencing UKC [PIANC, 2014]. With every wave, there is a certain statistical change of exceeding the UKC limit and hitting the bed. The accepted level of risk is based on the probability of occurrence times the financial and environmental consequences. A probabilistic calculation method can be applied to take these wave dynamics into account and determine a 'Dynamic UKC' (DUKC) policy. Several methods to calculate wave-response allowance are presented by PIANC, but the results differ widely [Onrust, 2018]. To determine wave-induced motion, vessel stability factors (dimensions, hull shape and the weight distribution), and real-time and forecasted wave climates, currents and wind speeds must be available. Also, vessel-specific and channel-specific prediction formulas are required [Parker and Huff, 1998]. Gucma et al. [2012] describe how such a DUKC system can be developed. In the future, more probabilistic design considerations are expected to be included in the vertical design of channels, such as uncertainties for vessel draught, bed level, tidal predictions and wave forecasts [PIANC, 2014].

As for the PoR, vessel movements are limited in the port, and this approach is only applied at the port entrance channel, the *Europoort* channel. PIANC [2014] guidelines also only apply the probabilistic approach for port entrance channels. For simplification, PIANC guidelines indicate that the DUKC is approximately equal to 15% of a vessel's draught in the approach channel. This background is provided for the completeness of this report, but there will not be further elaborated on this topic. This is a different study than designing bed levels inside a port. Moreover, the port entrance channel is very seldom the bottleneck in a route at the PoR [Interviews Port of Rotterdam, 2019-2020].

Deterministic and dynamic UKC (PoR)

Deterministic UKC calculations are based on generalised experiences from the past, which have been converted into a fixed vertical safety margin under all hydro-meteo and tidal conditions. The dynamic UKC calculations are based on live measurements data and predictions from validated models. RWS and PoR advise pilots to apply the DUKC in the port approach channel. In good and calm weather, this results in a smaller UKC than the deterministic UKC calculation. In bad weather, the dynamic UKC calculation will result in a larger and safer UKC than the deterministic one.

2.2 Existing developments

2.2.1 Sailing through fluid mud

Fluid mud consists of a high-concentration of fine suspended sediment particles combined with organic matter and can be found in estuaries and rivers[Kiricheck et al., 2018a]. In time, the fluid mud will settle and consolidate, unless it is stirred up again due to dredging activities or currents. The UKC of a vessel can be lowered if there is no danger of damaging the vessel while sailing through the upper part of a fluid mud layer. When sailing through the fluid mud layer and the water-mud interface (the upper part of the fluid mud layer) is used as the bed level, a negative UKC is applied. This is challenging because it is hard to detect the fluid mud layer with traditional acoustic measurement techniques. Also, internal waves (undulations) are generated that can hinder the controllability and manoeuvrability of a vessel [Kiricheck et al., 2018a].

It can be unclear to define the bed level of a channel if the bed consists of a mud suspension, because it is non-consolidated. Physical properties of the mud change over the depth in the zone between the consolidated bed and the water-mud interface. The unclear definition of bed and depth is solved by Kiricheck et al. [2018a] by defining a *nautical bottom* and *nautical depth*. Depending on local circumstances and application, the *nautical bottom* is defined by PIANC [2014] as: ”the level where physical characteristics of the bottom reach a critical limit beyond which contact with a vessel’s keel causes either damage or unacceptable effects on controllability and manoeuvrability”. Accordingly, the *nautical depth* was defined as ”the instantaneous and local vertical distance between the nautical bottom and the undisturbed free water surface”. These definitions are in line with The British Standards Institution [2013]. This concept is depicted in Figure 2.7.

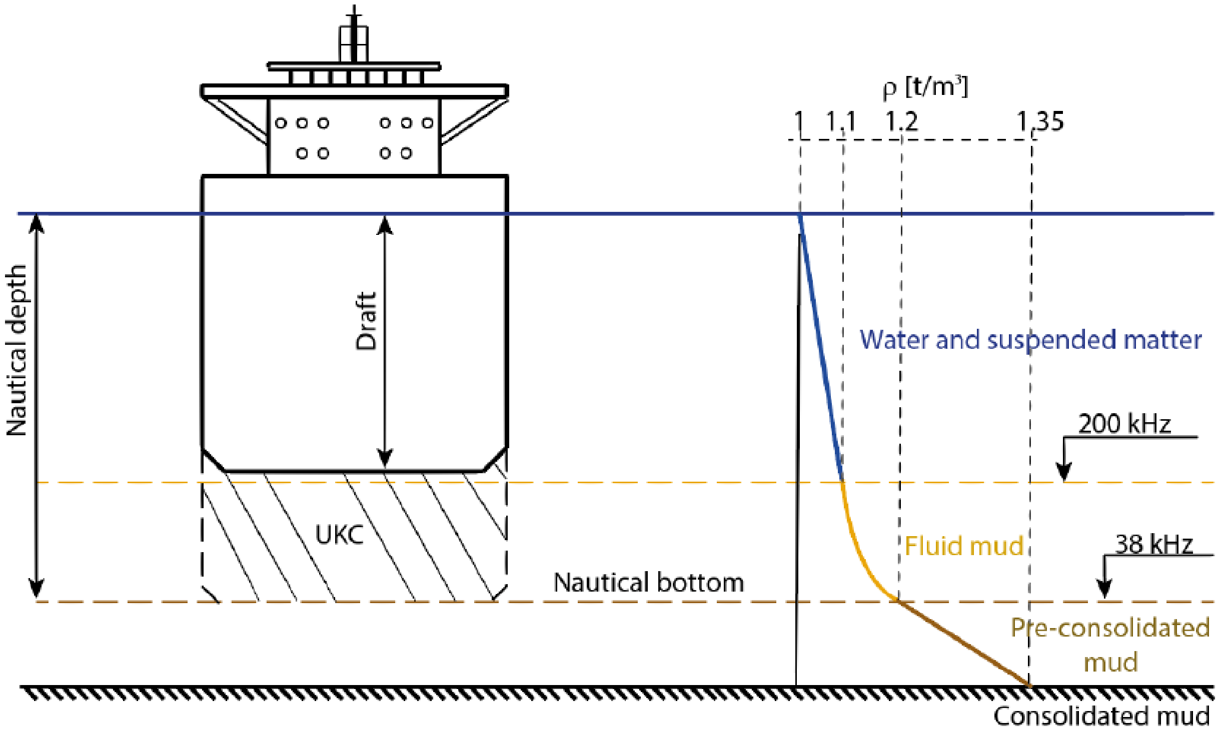


Figure 2.7: The nautical bottom concept [Kiricheck et al., 2018b]

Ports use different density criteria for the definition of the nautical bottom, see Table 2.1. It is impossible to define a universal value for the critical density [Vantorre et al., 2006]. The viscosity of the bottom material determines the strength and hence capability to damage a vessel or affect its manoeuvrability. Even if the density of two layers is the same: a layer with a high fraction of small particles has a larger viscosity than a layer with a low fraction of small particles. So for the same density of a layer, the viscosity can vary. Therefore, the strength depends on the exact, site-specific, structure of the mud content. Moreover, the strength of mud is complex because it is related to the consolidation and deformation history and is therefore also a function of time [Kiricheck et al., 2018b].

Country	**Port**	**Critical density ($kg/m3$)**
The Netherlands	Rotterdam	1200
Thailand	Bangkok	1200
Surinam	Paramaribo	1230
Belgium	Zeebrugge	1151-1347
China	Yangtze	1250
China	Liang Yungang	1250-1300
China	Yianjing Xingang	1200-1300
UK	Avinmouth	1200
France	Dunkirk	1200
France	Bordeaux	1200
France	Nantes-Saint Nazaire	1200

Table 2.1: Density criteria for bed level definition various ports [McAnally et al., 2007]

Echo sounding is a traditional technique to detect the bed level. The density criteria in Table 2.1 are the result of a series of full-scale experiments in 1980. The water-mud interface, detected by the echo-sounder, was used as a reference level for the UKC. It is a multi-beam technique, emitting frequencies. Small density gradients (water-mud interface) reflect high frequencies and relatively large density gradients (mud-soil boundary) reflect low frequencies. Unfortunately, this technique isn't capable to detect a clear difference between the fluid mud and consolidated bottom level [Kiricheck et al., 2018b]. Therefore, other surveying strategies have been developed. They are based on gamma-radiation, optical back-scatter and mechanical devices. These non-acoustical methods have common drawbacks. The measuring tools have to be in direct contact with the fluid mud layer, and the spatial resolution is limited to a 1D vertical profile. Therefore, these methods are often combined with echo sounding. The most accurate method so far is the nuclear gamma-radiation method [Kiricheck et al., 2018b]. The density measurements are based on X-ray and are linked to the acoustic data. Currently, this is used by the PoR and RWS. The different surveying techniques are currently being tested in various ports [Kiricheck et al., 2018a].

Reducing the safety margin underneath a vessel (UKC) by sailing through a fluid mud layer can have economic benefits for the port authority and shipping company, as less dredging is required and vessels can sail with a larger draught. On the other hand, a smaller UKC affects the manoeuvrability and safe navigation of a vessel. So a trade-off between safety and benefits has to be made.

Roukens [2016] has conducted such research using a decision support model based on a frame of reference approach by Koningsveld [2003], taking the objectives from end-users in terms of economy, ecology and safety into consideration. Three strategies were quantified and compared for a case of Delfzijl (a port in the North of the Netherlands): reduce dredging, increase draught or increase draught while maintaining the current UKC requirement. Reduced dredging turned out to be the most optimal strategy for this case, amongst others because relatively small vessels visit this area. However, this suggestion was not implemented because the port authorities had no means to assess the strength of the nautical bottom and corresponding vessel behaviour.

2.2.2 Digitisation and data availability

The maritime sector is a traditional industry where digitalisation has started slowly [Inkinen et al., 2019]. Integration of digital applications can make daily processes more efficient, which will lead to cost savings. Digitalisation leads to an increase in the storage and usage of data. This has resulted in an emerging term: Smart Ports. A Smart Port is a port that uses automation and innovative technologies including Artificial Intelligence (AI), big data, Internet of Things (IoT) and blockchain to improve its performance [Port Technology, 2019].

The PoR is one of the most advanced ports in the world. It has been awarded by the World Economic Forum, for the seventh consecutive time, as the 'best port infrastructure of the world'. Digitalisation is required for more efficient use of the infrastructure. The PoR digitisation initiatives mainly concern better control and management of the port and improved insight into efficiency of logistic processes. The data & digitalisation projects mentioned in this section are based on: Port of Rotterdam [2020a] and Interviews Port of Rotterdam [2019-2020].

HaMIS

The PoR has developed a harbour management system called HaMIS (Harbour Master Management Information System). HaMIS is used for operational planning and to guide vessels calling at the port. It allows the port authority to live-track all shipping activities. Vessels have to provide information about their type of cargo, destination, design draught and actual draught. They have to do this prior to entering the port and before and after (un)loading at a berth. The PoR has been storing this live data in a database since 2012. Now that a few years of data has been collected, the possibility has arisen to analyse this data.

Storage of AIS signals

The PoR has been storing Automatic Identification System (AIS) signals transmitted by vessels in the port to be able to analyse vessel's trajectories. Moments in time when a vessel passes a certain line in the port are stored. Figure 2.8 presents an overview of these lines.

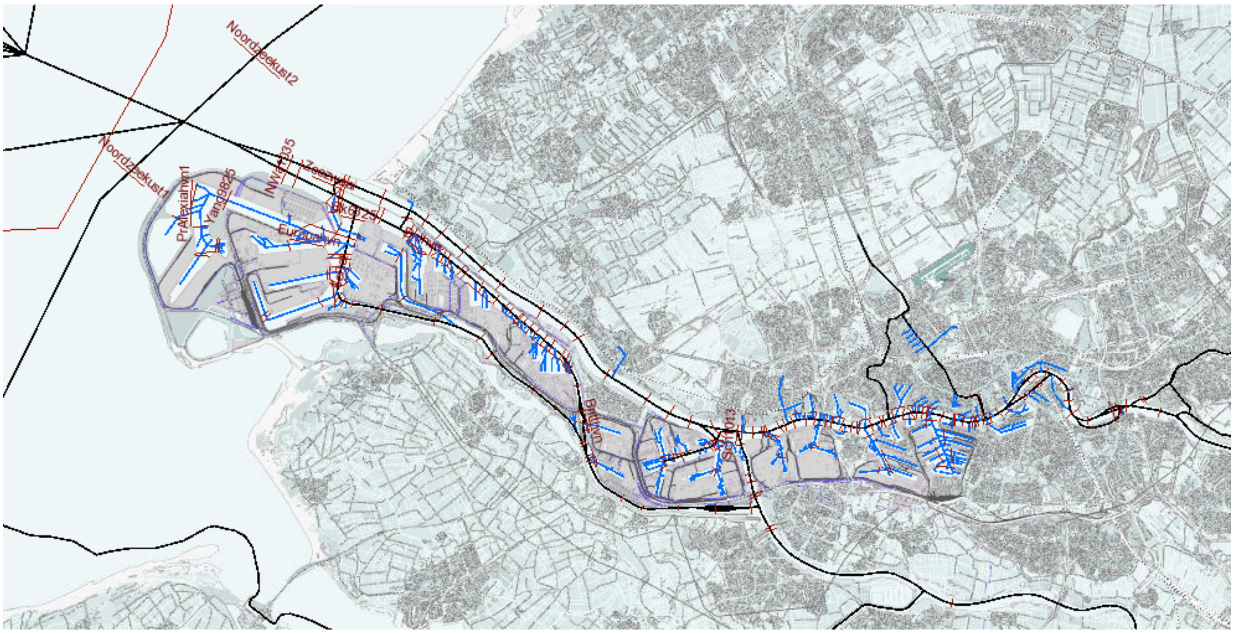


Figure 2.8: Passing lines for which AIS data are recorded in the PoR

PortXchange (Pronto)

PortXchange started as the Pronto (Ports Rendezvous Of Nautical and Terminal Operations) project in Rotterdam. PortXchange is an application that can be used by the port community (shipping lines, terminals, agents and other service providers) to optimally plan, execute and monitor all activities during a port call. It is based on standardised data exchange. PortXchange can be used in exchange for a fee or data.

Avanti

The web-portal Avanti (Access to Validated Nautical Information) focuses on available water depths and accessibility. A test version was online for a while but is now offline. The new version is expected to be released in September 2020. Avanti provided insight into expected tidal variations and associated accessibility. The user had to insert draught and UKC. Subsequently, Avanti indicated at what time UKC policy would be violated. The new release will include a 24/7 alarm functionality. If there is a significant difference in wind, tide or traffic activity than expected, there will be a notification. Increased traffic activity is good to know in order to pay more attention to mooring lines. Moreover, sounding data (bed level and depth) will be published in Avanti on the same day it has been measured.

NAIADE - 'Weather & Tide' dashboard

NAIADE is the 'Weather & Tide' dashboard of the PoR. The dashboard provides actual, predicted and astronomical hydro-meteo information for maritime professionals within the PoR area. The associated data is stored by the PoR and can be used for analyses. The data is obtained and managed in cooperation with *Rijkswaterstaat*. The *Operationeel Stromingsmodel Rotterdam* (OSR) is included in the dashboard. The OSR model provides information on expected water levels and currents in the port. An impression of the dashboard is presented in Figure 2.9.

NRDP: 3.17 m/s (2 BFT)
gust: 3.54 m/s

Last update: 16:25:20 WEDT

PHW and PLW | HOEK

	HOEK	cm (NAP)
PLW	Tu 15:00	-52
PHW	Tu 20:30	95
PLW	We 03:00	-85
PHW	We 09:00	98
PLW	We 15:30	-58
PHW	We 21:30	88

Last update: 16:25:19 WEDT

PSLW | HOEK PSLW | BOTNM PSLW | BOER

	HOEKNWW
PSLWDA	Tu 06:07
PSLWDA	Tu 11:20
PSLWDA	Tu 18:37
PSLWDA	Tu 23:17

Last update: 16:25:19 WEDT

Figure 2.9: Impression of the NAIADE - 'Weather & Tide' dashboard

DTP

Dynamische Tijpoort Viewer (DTP), 'Dynamic Tidal-gate Viewer', is an application made to assist HCC with the determination of tidal windows. It presents accessibility moments for port basins up to 36-hours in advance. A vessels' dimensions and trajectory are required input. Accessibility is subsequently based on guidelines for tide-bound vessels; Port of Rotterdam: DHMR & HCC [2020]. The required hydro-meteo data is obtained from OSR. An example is provided in Figure 2.12 (Section 2.3.2).

Dredging-decision-model

The PoR is developing a model to support the decision-making process of prioritising dredging maintenance areas in the port. It is a static model that considers MBL's only. It doesn't consider variables such as actual water levels. For every route in the port (from sea to berth), is mapped where the passageway is minimal (based on MBL's). This is determined for each route; the results are subsequently overlaid to identify low and high priority dredging maintenance areas. Hence, the result is also based on the occupation of channels.

Optimised dredging: improving nautical infrastructure

The horizontal design (top view shape) of channels, and hence maintenance areas, are currently being optimised by the PoR based on AIS vessel tracks. This provides better insight into where, and how often, vessels sail in the port. Dredging sections are adapted accordingly to reduce unnecessary maintenance costs. An example of this analysis, at the *Beerkanaal* in the *Maasvlakte 2*, is presented in Figure 2.10. The red triangle in the figure reveals an area where vessels sail very seldomly.

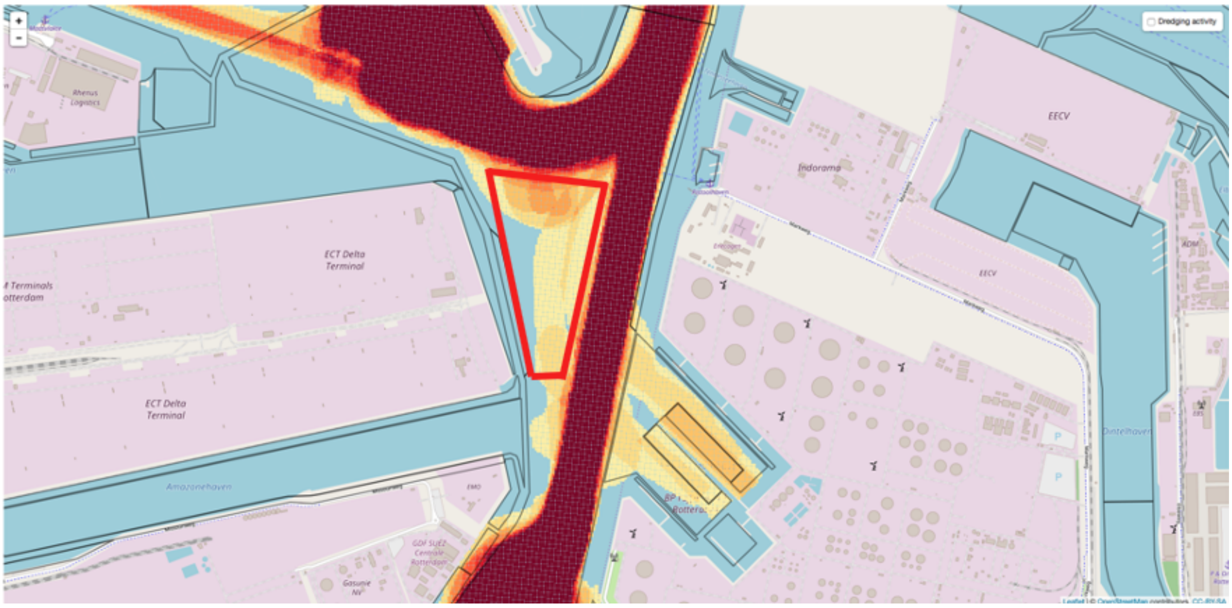


Figure 2.10: AIS vessel density tracks analysis on *Beerkanaal* (*Maasvlakte 2*)

2.3 Port of Rotterdam

The Port of Rotterdam is a port with a great history that has had to adapt enormously. It is by far the largest port in Europe, in terms of size and throughput. From 1962 till 2004, it was even the busiest port of the world. Now overtaken by mainly Asian ports, it is the 10th largest port worldwide. The PoR offers excellent accessibility for sea-going vessels and is the only port in north-western Europe that is able to handle the largest vessels (with draughts up to 22.6m) [Port of Rotterdam, 2019b]. Moreover, it has a strategically important position; it is very well-connected to Europe's largest cities and industrialised centres. Therefore it has become the economic vein of Europe; essential for Europe's trade and economic activities.

The port was already an important seaport in the middle of the 19th century, mainly due to transport of goods between England and Germany. However, the competitive position of the port deteriorated due to the poor connection to the open sea as vessel sizes increased. The delta of the *Rijn-Maas* was to branched, river arms were fairly shallow and silted up easily. In 1863, therefore, a bill was passed to construct a channel between Rotterdam and the North sea suitable for large sea-going vessels; the *Nieuwe Waterweg*. When the construction of the *Nieuwe Waterweg* channel was finished in 1872, the accessibility and hence demand of the port increased again. This triggered and enabled the further growth and development of the port as the most important port in Europe. Throughout the course of history, the port has constantly been developing to maintain its leading market position. This development is depicted in Figure 2.11.

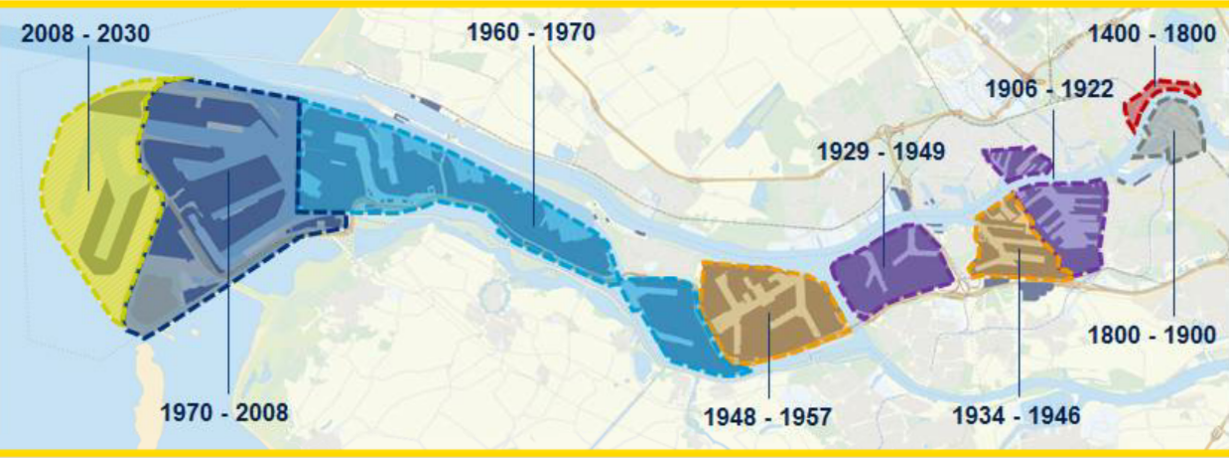


Figure 2.11: Historical development Port of Rotterdam [Port of Rotterdam, 2019b]

2.3.1 Departments and actors

"The Port of Rotterdam Authority manages, operates and develops the port and industrial area of Rotterdam and is responsible for maintaining a safe and smooth handling of all shipping" [Port of Rotterdam, 2019b].

This section briefly discusses the departments and actors that are directly relevant to this study.

Two parties are responsible for the maintenance dredging in the PoR area, the Dutch governmental organisation *Rijkswaterstaat* (RWS) and PoR. Roughly can be stated that RWS is responsible for maintaining bed levels in the main channels (like the *Nieuwe Waterweg*, *Oude, en Nieuwe Maas*), while the PoR is accountable for bed levels in the port basins. The division Asset Management (AM) of the PoR is responsible for maintaining bed levels and the corresponding dredging policy.

The Division Harbour Master of Rotterdam (DHMR) is responsible for the safe, efficient and clean navigation of vessels in the PoR nautical management area. DHMR performs a public task. It advises on projects related to nautical infrastructure and sets nautical conditions. DHMR has determined design guidelines and evaluation procedures for the dimensioning of newly-build or adaptable nautical port infrastructure. The nautical experts design a theoretical bed level to provide sufficient accessibility and safe navigation. The Harbour Coordination Center (HCC) is a more operational department. HCC assesses the accessibility for vessels calling at the port. It analyses traffic, berth availability and (expected) water levels.

The port's clients are its users. These are terminals and shipping lines. The commercial department is in contact with them. This department works with customers to develop new concepts and to build clusters of companies. This department is focused on retaining existing customers, finding new ones and identifying unknown customers.

2.3.2 Port basin accessibility

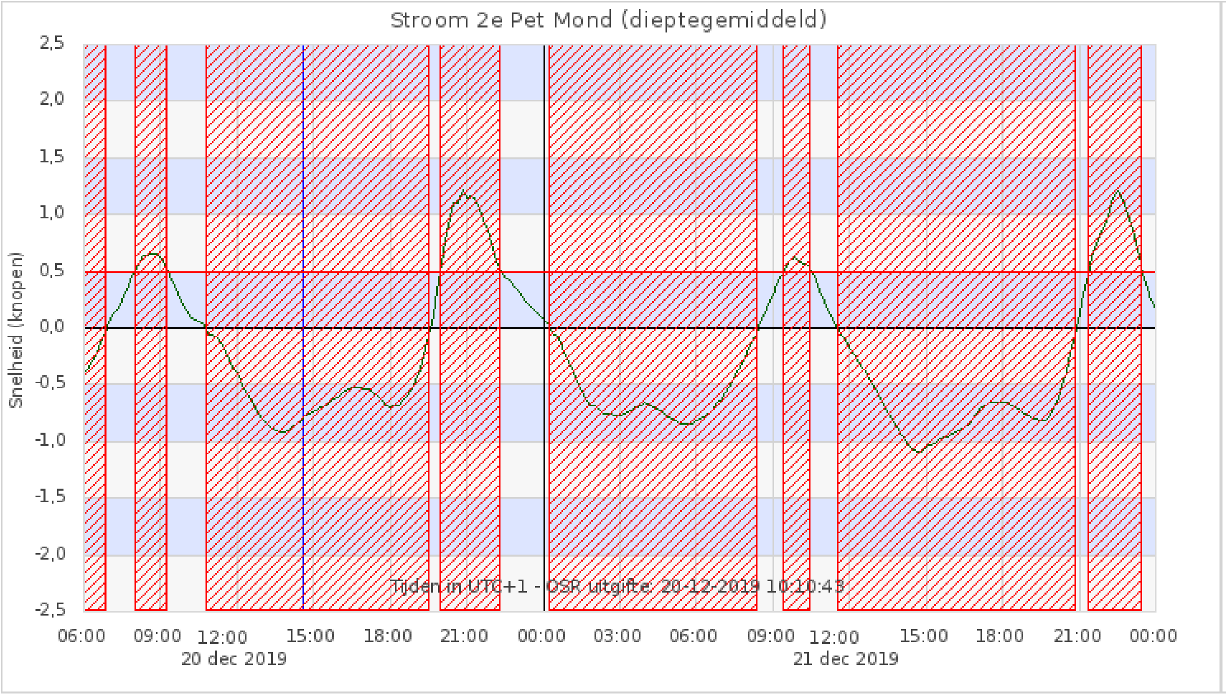
If a berth is occupied or if there is too much traffic on a trajectory, a vessel has to wait outside the port (at sea). This is not directly related to the vertical design of channels.

As described in Section 2.1.1, a vertical and horizontal tidal window can be applied for large-draughted vessels. In the PoR, these two windows are merged into one tidal window. Tidal windows are mainly determined based on experience in the PoR. HCC and pilots know from experience which currents allow safe manoeuvrability into a basin. These currents have been chosen in such a way that an appropriate water level is often present. These experiences and guidelines for accessibility are (iteratively) updated in "Port of Rotterdam: DHMR & HCC [2020]". These guidelines are based on agreements between the *Loodsencorporatie Rotterdam-Rijnmond* (LRR), which is a pilotage corporation, and the Harbour Coordination Center. These agreements serve to outline the conditions under which pilotage (in Dutch: *loodsen*) of sea vessels can take place. In practice, HCC first examines the horizontal tidal window and subsequently checks the local water levels to see if they fit [Interviews Port of Rotterdam, 2019-2020], which is often the case because the tidal windows are chosen to have an overlap in the vertical and horizontal tidal windows. To clarify these windows separately:

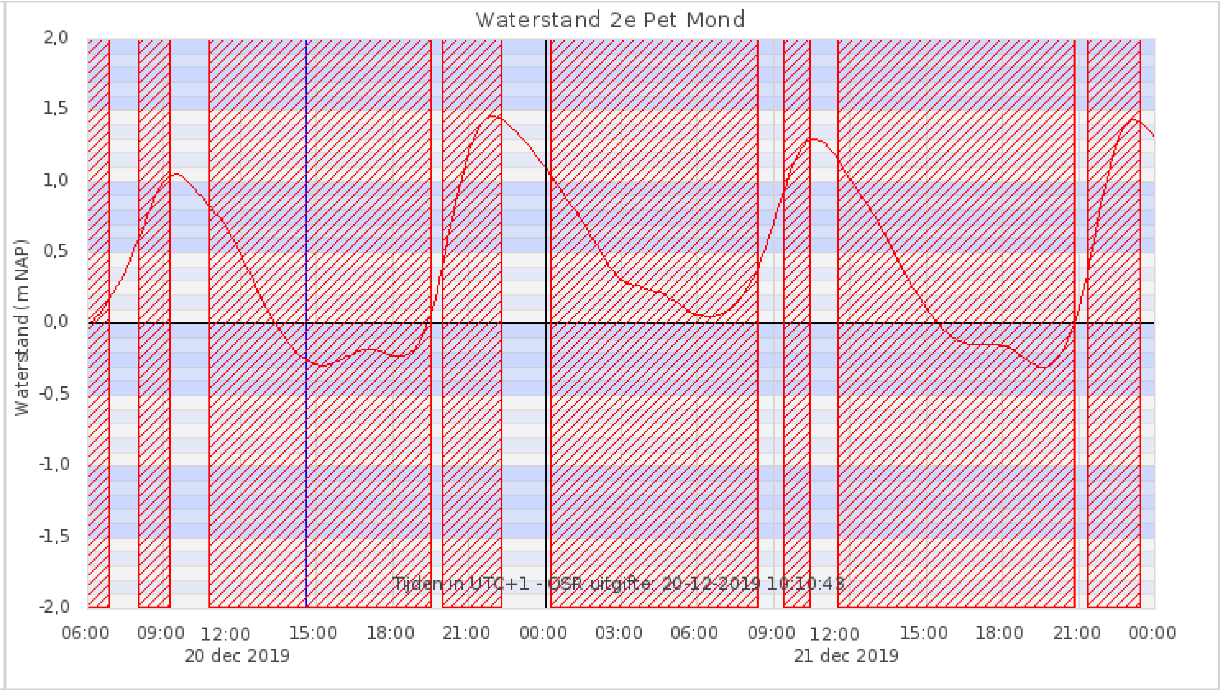
Vertical tidal window
The wet infrastructure in Rotterdam is designed to provide accessibility with 99% of the tidal cycles (often during high tides) for tide-bound vessels and 99% of the time for non-tide-bound vessels. High accessibility is of economic importance. For outbound tide-bound vessels, there isn't a predetermined percentage.

Horizontal tidal window
Currents can be too strong at a certain period in the tidal cycle to allow certain vessels to navigate safely. This results in an accessibility restriction, which is also called the 'current window'.

So for safe navigation, there should be an overlap in these windows to enter or leave a port basin. The PoR has developed a 'Dynamic Tidal-gate Viewer' (DTP) to provide live accessibility information to vessels. An example is presented in Figure 2.12, for an incoming vessel with a draught of 12.5m sailing to the *2e Petroleumhaven.* The maximum allowed current during flood equals 0.5 *knopen* and during ebb 0 *knopen* in this port basin. Large-draughted vessels often enter a port basin around high-water slack, which is when the horizontal tide is the lowest and the water level is high [Interviews Port of Rotterdam, 2019-2020].



(a) Horizontal tidal windows (currents)



(b) Water levels corresponding to horizontal tidal windows

Figure 2.12: Horizontal tidal accessibility-windows for a vessel with a draught of 12.5m sailing to the *2e Petroleumhaven* on 20-12-2019 (basin is not accessible in red areas)

2.3.3 Water depth policy

A depth and draught definition figure used by the PoR is provided in Appendix B.1.

This section is based on the DHMR guidelines [Port of Rotterdam: DHMR, 2019]. MBL design approaches are included in these guidelines. The division Asset Management (AM) is responsible for maintaining these MBL's and the corresponding dredging policy. Moreover, the design of channels cannot always be dealt with in a simple generalised approach or formula, as it depends on many (local) factors. Hence, there may be deviated from the described guidelines in the design process. Thorough research and practical knowledge of the local conditions and vessel manoeuvring properties may be necessary; to determine a design that guarantees the safe and smooth handling of vessels.

Reference level (ALAT) and sinkage (FWA)

As described in Section 2.1.1, LAT has internationally become the normative low-water level in tidal port-areas and sea access channels since 2007. It is the lowest predictable water level, so all astronomical predicted water levels are higher than LAT. In the PoR estuary, river discharge also influences the water level. For this reason, an Approximately LAT (ALAT), also known as the agreed low water, is referred to in the PoR. In addition, lower water levels than ALAT can occur due to wind and air-pressure influences. These are the so-called hydro-meteo effects.

The wet infrastructure in Rotterdam is designed to provide for 99% of the time or high waters accessibility for the largest-draughted vessels. The ALAT water level is used as a reference level for designing a channel. However, ALAT is statistically underestimated about 1 to 2% of the time and about 10% of the number of low waters due to the previously mentioned hydro-meteo effects [Port of Rotterdam: DHMR, 2019]. The chance that a low tide is lower than ALAT is therefore larger than 1%. Hence, an extra hydro-meteo margin is added when designing a channel to ensure 99% accessibility.

The aforementioned HME margin is therefore an extra margin, by which the percentage of the number of low waters that are lower than ALAT is reduced to 1%. This margin turns out to be 0.3 m for all subareas in the PoR and is used for both sea and inland shipping [Port of Rotterdam: DHMR, 2019]. So this reduces the number of low waters that are more than 30 cm below ALAT to 1%, which corresponds to approximately 7 (of the approximately 700) low waters per year.

The ALAT values (relative to NAP) are presented in Appendix B.3 per subarea in the PoR, which are used for the vertical design of channels. In addition, the Fresh Water Allowance (FWA) values for subareas in the port are provided. The FWA is a draught increase (sinkage) of the vessel due to the difference in specific mass between fresh and salt water. A vessel has less buoyancy and therefore a larger draught in fresh water than in salt water. The margin is expressed as a percentage of the static saltwater draught of a vessel. This margin (in meters) is included in the design of the wet maritime infrastructure.

Underkeel Clearance policy

The PoR has UKC policies for various sections (fairway, basin and berth). The UKC-policies are presented in Appendix B.4. Again, this is the policy inside the PoR, a different DUKC-policy is applied outside the port (in the approach channel). The UKC policies are based on the PIANC [2014] build-up, which was presented in Figure 2.1. Figure 2.13 depicts the distinction of approach channel (approaches), fairway, basin and berth for a container vessel on the *Prinses Amaliahaven* trajectory. The UKC at fairway equals 1.0 m and basin 0.5 m. Only at berth is a distinction made between whether a vessel will arrive on a long term ($>$ 36 hours) or at short term ($<$ 36 hours). For short term, the depth at berth can be based on recently sounded depths. This reduces uncertainties; hence 0 m UKC at berth becomes negotiable given the fluid-mud bed in the PoR. For long term, 0.3 m UKC is considered. Detailed examples of how these UKC policies were build-up are also provided in Appendix B.4.

The UKC is maintained in the operational policy and serves as a minimum UKC for clients. The UKC policies are underpinned by UKC factors as prescribed by PIANC but are actually mainly

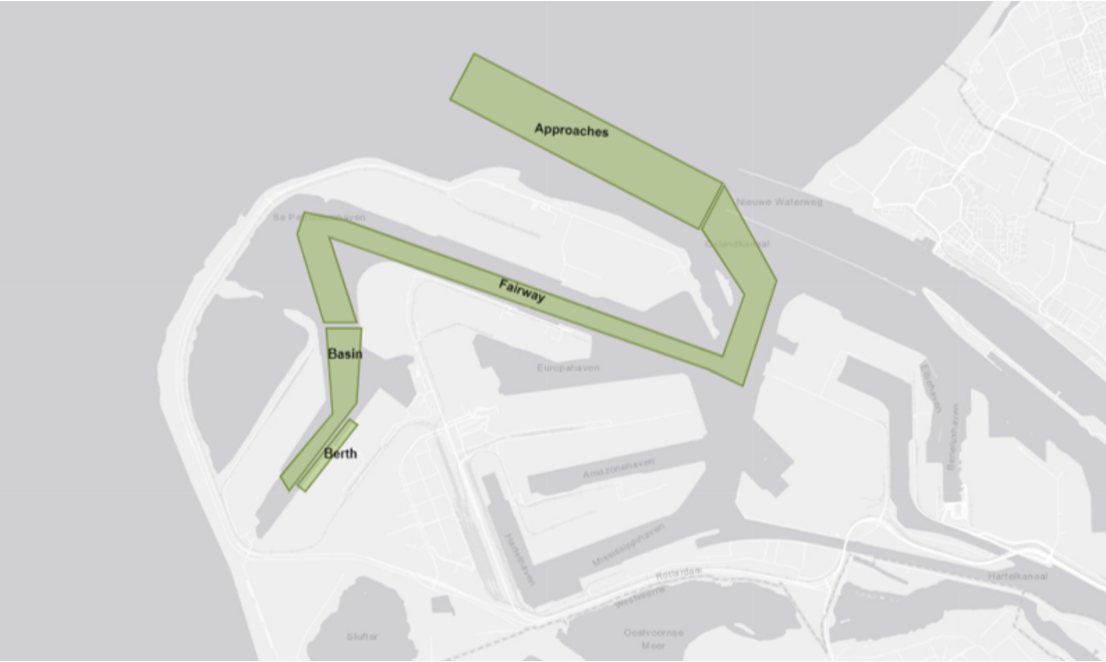


Figure 2.13: Port sections on *Prinses Amaliahaven* trajectory

based on pilot experiences [Interviews Port of Rotterdam, 2019-2020]. This is understandable given the complex physics of vessel motion in shallow waters. Interviews with experts have shown that this will most likely remain an issue of experience and iteration [Interviews Royal HaskoningDHV, 2019-2020].

Shipping lines and port authorities can have a different perspective on UKC factors to consider and hence policy. Shipping lines sometimes sail with a safer margin than a port imposes on them because they prefer their own for safe navigation. A larger UKC (for safer navigation) is achieved at the expense of cargo. Some shipping lines also include allowances for depth data, water level uncertainties and water salinity variances in their UKC build-up. In the PoR, the former is already included in the dredging policy and the latter two in the vertical design of waterways. So, these are unnecessary safety margins.
Figure 2.14 presents the perspective of a PoR client on UKC. The allowances vary per port and depend on the reliability and degree of uncertainty of each factor in a port. Please note: this build-up differs from the build-up as proposed by PIANC (Figure 2.1). Figure 2.14 has deliberately not been adapted to PIANC's structure and definitions to show the differences.

The PoR already takes account of these allowances as follows:

- Allowance for depth data uncertainties:
  Any uncertainties in the bed level are taken into account in the dredging policy (see section 2.3.6)
- Allowance for water level uncertainties:
  There is an uncertainty in forecasted water levels due to hydro-meteo effects, this is accounted for in the determination of the maintained bed level (see next section)
- Allowance for prevailing sea & swell conditions:
  Wave-action is very limited and negligible inside the PoR
- Allowance for list and/or heel(turning/wind):
  Is incorporated in the UKC-policy

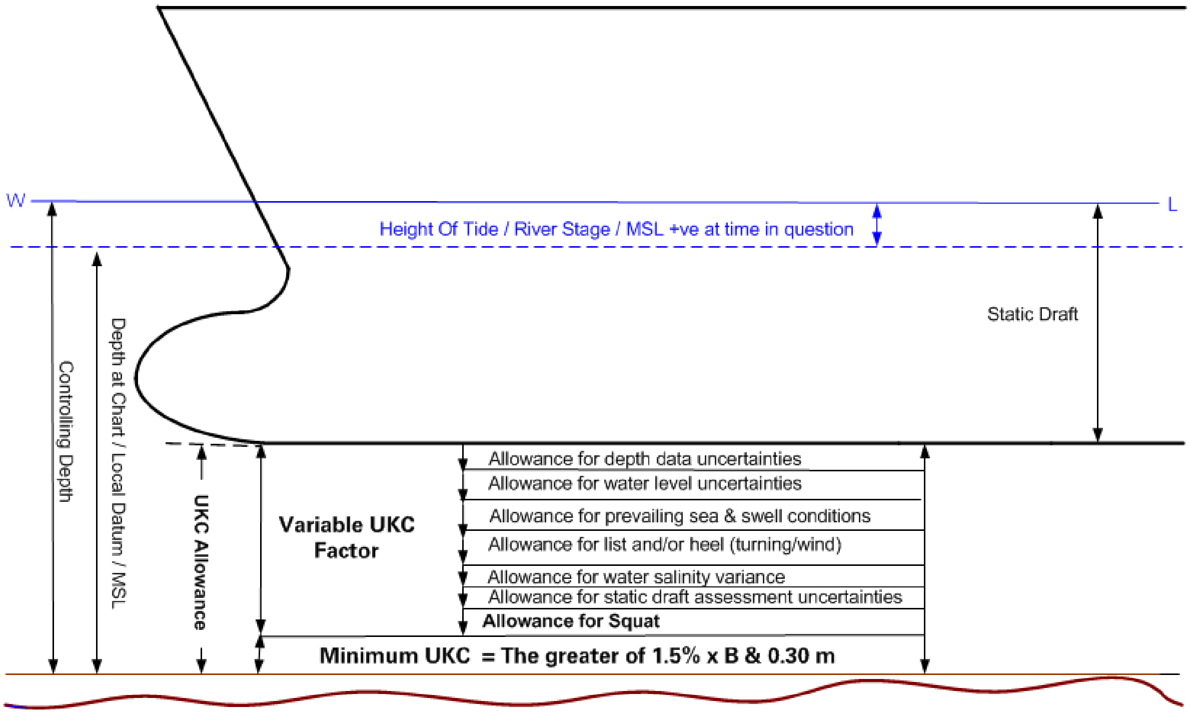


Figure 2.14: A large PoR client's perspective on variable UKC factors

- Allowance for water salinity variance:
  Is accounted for in the determination of the maintained bed level (see next section)
- Allowance for static draught assessment uncertainties:
  Not taken into account, there is assumed that clients provide a reliable draught
- Allowance for squat:
  Is incorporated in the UKC-policy

2.3.4 Maintained depth and maintained bed level

The maintained depth is a safe navigable depth. It is the minimum depth the port authority strives for to facilitate in a channel (excluding extreme conditions). This MD is achieved by maintaining a certain bed level. At the PoR, it is also called the Nautical Guaranteed Depth (NGD), contract depth and dredger-atlas-depth. NGD is a literal translation from Dutch (*Nautisch Gegarandeerde Diepte*). The term 'contract depth' is often used by clients.

As mentioned before, preference is given to refer to MBL's instead of MD's in this study. For completeness and to explain the difference again, the following formula has been written down.

$$MD = h_{NAP,design} + MBL_{NAP} \tag{2.1}$$

Where:

MD = Maintained Depth [m]
$h_{NAP,design}$ = water level w.r.t. NAP corresponding to a design accessibility [m]
MBL_{NAP} = Maintained Bottom Level w.r.t. NAP [m]

Next, the two most recent PoR's MBL design approaches are described. They are approximately eight years old [Interviews Port of Rotterdam, 2019-2020]. At last, an older design approach is described for the historical context. Moreover, the MBL is expressed negatively with respect to NAP and is rounded up to decimeters. Please note: the designed theoretical bed level is discussed in this section. In practice (operational), live measured, predicted bed and water levels are also considered to check the accessibility. These values are obtained with the *Operationeel Stromingsmodel Rotterdam* (OSR) model.

MBL design on low tide, without accessibility restrictions

For sea-going vessels without accessibility restrictions (for 99% of the time), the MBL of a channel is determined by the PoR with the formula below. The build-up of the vertical profile used for this design approach is depicted in Figure 2.15. The extreme low water level is 30 cm (HME) below ALAT and is exceeded by 1% of the low waters [Port of Rotterdam: DHMR, 2019].

$$MBL_{NAP} = T + (FWA * T) + UKC + HME + ALAT_{NAP} \tag{2.2}$$

Where:

MBL_{NAP} = Maintained Bottom Level w.r.t. NAP [m]
T = draught for which a channel has been designed (in salt water) [m]
FWA = Fresh Water Allowance [%]
UKC = minimum required UKC as imposed by PoR [m]
HME = Hydro-Meteo Effects [m]
$ALAT_{NAP}$ = Approximately Lowest Astronomical Tide relative to NAP [m]

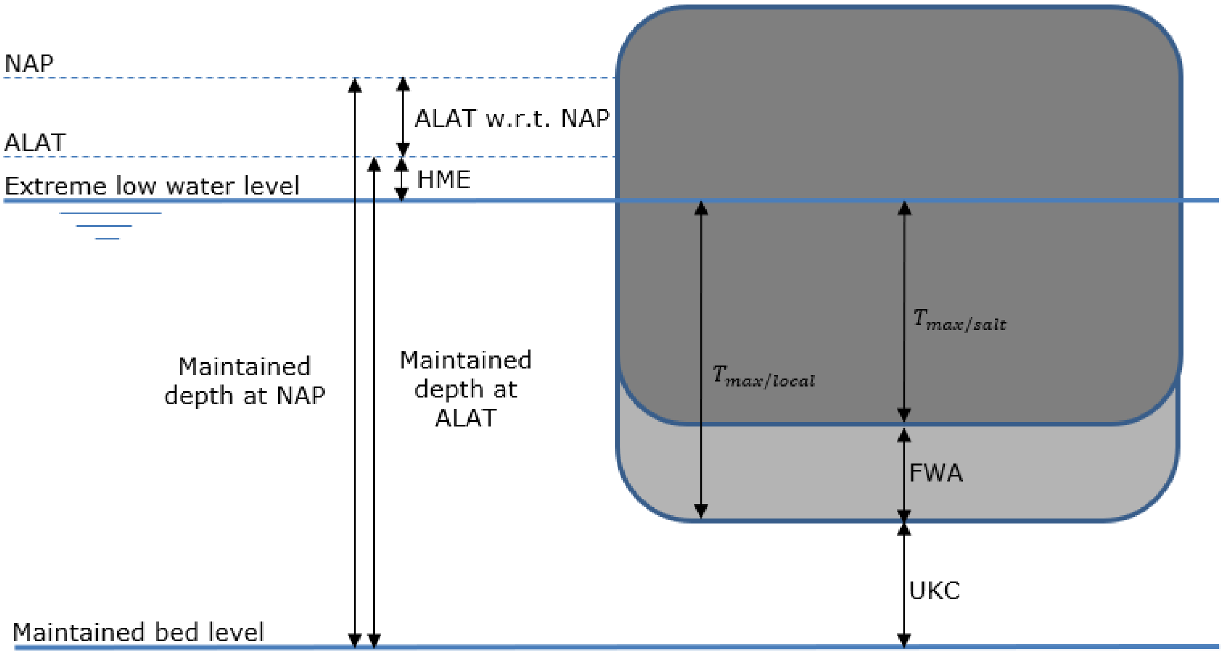


Figure 2.15: Vertical design in relation to low water levels (for non-tide-bound vessels)

MBL design on high tide, for tide-bound vessels

Tide-bound vessels sometimes use high water periods to enter the port with more draught. The MBL for a channel with tide-bound vessels sailing on high water levels is determined with the formula below. The corresponding build-up of the vertical profile is presented in Figure 2.16. This approach has only been applied once in the PoR, for the recent deepening of the *Nieuwe Waterweg*.

$$MBL_{NAP} = T + (FWA * T) + UKC - (HW_{99\%} - \Delta H) \tag{2.3}$$

Where:

$HW_{99\%}$ = measured high water level (w.r.t. NAP) that is exceeded by 99% of the high water levels [m]
ΔH = lowering of water level during transit [m]

The $HW_{99\%}$ is a statistically determined (measured) water level that is exceeded by 99% of the high waters. It is a measured water level, so it includes hydro-meteo effects (wind set-up and air pressure influences).

The lowering of the water level during the travel time to a berth is accounted for with the parameter ΔH. This margin is applied in the design of a channel, because water levels can lower during the voyage of a vessel. This margin increases as travel time increases and can vary per route.

Values used for $HW_{99\%}$ and ΔH by the PoR are provided in Appendix Table B.1 and Table B.2.

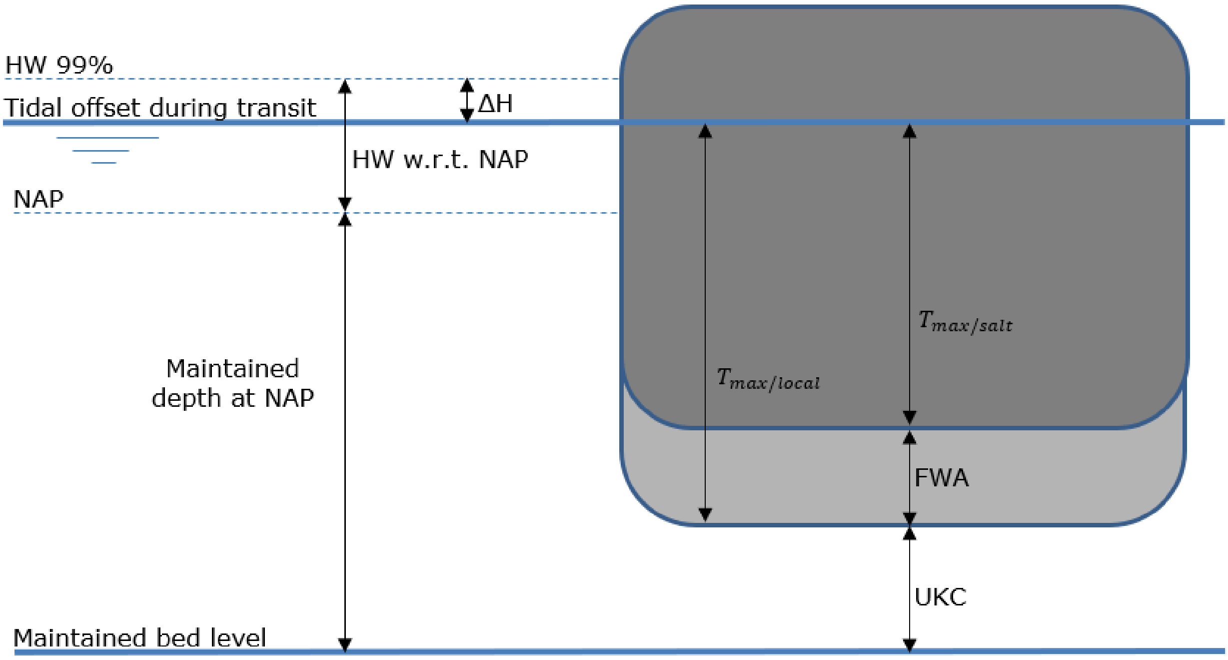


Figure 2.16: Vertical design in relation to high water (for tide-bound vessels)

Old PoR MBL design approach

In the past, the *Rottepeil* was used as the reference level when designing the bed level of a channel in the PoR [Interviews Port of Rotterdam, 2019-2020]. This is the extreme low water level in the city centre of Rotterdam, which equals -0,65m NAP. This is the reason why many MBL's in the PoR equal 65cm behind the comma. Even the MBL's of channels in the *Maasvlakte 2*, which was designed in 2006, have this 65cm behind the comma and are based on the *Rottepeil*. The MBL of the Yangtzekanaal, for example, equals NAP - 19.65m. The design draught of vessels handled in *Maasvlakte 2* equals 17m.

The design formula looked something like this [Interviews Port of Rotterdam, 2019-2020]:

$$MBL_{NAP} = T + UKC + ALAT_{NAP} \tag{2.4}$$

With:

$T = 17$ or 18 m
$UKC = 1$ or 2 m
$ALAT_{NAP} = 0.65$ m

2.3.5 Port income

The PoR has two main sources of income. Income is used for maintaining channels (dredging) and quays.
Firstly, the lease of land to terminals. Terminals pay the PoR for the facilitated MBL at a berth, the price increases for every 10 cm extra depth. The PoR and RWS subsequently maintain the associated waterways. If a terminal wants to receive larger-draughted vessels, the PoR will consider whether this is desirable and possible.
Secondly, vessels berthing at the PoR pay port dues. The port dues are composed of a vessel-part and throughput-part. The larger a vessel (in gross tonnage m^3), the more it has to pay, because it uses more depth and has a larger impact on the quays. Also, the more cargo a vessel transfers at a terminal, the more port dues it has to pay. There is not a direct relation between vessel waiting times and port dues, the PoR does not compensate a vessel if it has to wait outside the port or at a berth due to dredging maintenance works or low water levels for example [Interviews Port of Rotterdam, 2019-2020]. There is only a direct relation if a vessel decides to go to another port instead of the PoR (client loss). For a vessel, waiting time is very costly due to fuel, chartering, crew, demurrage costs and costs of opportunity. So the PoR wants to prevent this as much as possible from happening to keep clients satisfied and prevent reputational damage.

2.3.6 Sediment management

Annually, 12-15 million m^3 material is dredged in the PoR to provide accessibility for vessels with the largest draughts [Kiricheck et al., 2018c]. The PoR estuary area is influenced by the *Rijn* and *Maas* rivers from the east and by the North Sea from the west. This results in both marine and fluvial types of deposited sediment.

The channels are monitored by two surveying vessels sailing through the port area five days per week during regular working hours. As described in Section 2.2.1, a multi-beam echo-sounder is used in combination with a gamma-radiation method (called the DensX profiler) to map the bed levels. This data is subsequently integrated into the Dredging Atlas, where the measured bed levels are compared to the MBL. If the measured bed level is smaller than the MBL, dredging is required in that area. RWS is responsible for maintaining bed levels in the main channels, and the PoR is accountable for the bed levels in the port basins.

Three types of dredging vessels are used for maintaining the channels; the trailing suction hopper dredger, bed leveller and grab dredger. This is because specific dredging techniques are required for certain port basins and soils. Dredging is performed by various contractors, to ensure continuity and to prevent monopolism (reducing costs) [Kiricheck et al., 2018c]. The asset management department of the PoR directs the contractors when and where to dredge. The area for relocation of the dredged material depends on the chemical and physical quality of the material. The quality is annually being monitored. Clean dredged material is relocated to sea and contaminated material to the Slufter (a confined disposal facility on the *Maasvlakte*).

So RWS and the port authority maintain the bed level of channels. Clients pay the port authority to facilitate this MBL. To reduce dredging activities, dredgers often over-dredge. This means the actual bed level can be below the MBL. On the other side, the design draught is not always reached in practice because vessels are not always fully loaded. Therefore, the available water depth can often be larger than required in practice. The port is aware of this fact and has less priority to have channels dredged where mainly vessels visit with draughts smaller than the design draught [Interviews Port of Rotterdam, 2019-2020]. The actual bed level can become smaller than the MBL in this case (under-dredging). Now, this decision to dredge less and have a smaller priority to comply with the MBL in certain channels is based on the experience of dredgers and is not based on data or calculations. If a vessel with a large/design draught announces itself (which is at least 24 hours in advance) and the MBL isn't available, urgent dredging must take place to comply with the contractual agreements. Urgent dredging is more costly than normal maintenance dredging.

There is some ongoing research to apply a water injection dredging-technique at the PoR [Kiricheck et al., 2018c]. The goal is to mobilise weak fluid mud layers by liquefaction and make it flow into a man-made pit. Based on experiments, it is concluded by Kiricheck et al. [2018c] that this can be a feasible, cost-effective dredging strategy.

2.4 General impact of adjusting the MBL

Decreasing the MBL

If the bed level is increased (by reducing dredging activities) and vessels keep sailing with the same draught, the UKC decreases and the risk of hitting the bed increases. Consequences may include groundings, repair costs, insurance claims, lost bookings and service, and even loss of life [PIANC, 2014]. However, if vessels are informed, they will keep sailing with the imposed UKC policy. Hence, they will sail with less draught, reduce speed (to reduce squat) or wait for higher water levels. Reducing speed causes traffic jams and hinders transit in the port. So a shallower maintained bed level will result in a vessel draught reduction and/or a channel accessibility reduction.

Increasing the MBL

The opposite is true for deepening the bed level; more dredging is required to allow vessels with larger draughts and/or the channel accessibility may increase. It may increase because a channel may already be accessible at all times. Quantifying the added value of deepening the bed level is complex. The PoR had had an extensive traffic study performed by *RIGO Research en Advies BV [2009]*, to try to quantify the economic damage if the *Maasgeul* would not be deepened. Despite their extensive research, the presented forecasts and expectations for the future (performed in 2009) have not been fulfilled [Interviews Port of Rotterdam, 2019-2020]. Their expectations of future market-demand and increasing vessel sizes were incorrect.

Economic

The economic impact of adjusting the MBL is not that rational [Interviews Port of Rotterdam, 2019-2020]. It is hard to compare costs and benefits. The benefits (of less dredging), for example, are for the port authority and the costs (of increased waiting times or sailing with less draught) are for the business community. It isn't on the same balance.

Dredging

It is a one-time gain if a port has to dredge less, but as the bed level comes closer to the morphological equilibrium, it is in theory expected that the sedimentation rate could also decrease. However, the sedimentation process is so dynamic (due to weather, tides, currents, water density and shipping) that this is not demonstrable or measurable ([Interviews Port of Rotterdam, 2019-2020]). Moreover, dredging has negative a negative impact on the environment [Manap and Voulvoulis, 2016].

Conclusion

In conclusion, the following assumption is made based on interviews: the current safe and smooth accessibility of channels should not decrease to not damage businesses. It is still interesting to investigate structural over-depths of channels to reduce dredging activities (and hence costs) and bottlenecks to ensure the desired accessibility percentages are achieved.

2.5 Conclusion

This chapter has studied topics related to MBL's and accessibility. By doing so, the sub-research questions below can be answered.

How are maintained bed levels determined, and what are the opportunities for improvement?

PIANC guidelines have broad international support and can be considered as a generally accepted approach. The MBL can be determined by using the PIANC build-up as presented in Figure 2.1. PIANC guidelines have broad international support and can be considered as a generally accepted approach. However, these guidelines are designed to facilitate safe navigation and can be used everywhere. Because they are so general, the results are often conservative and can vary widely ([Onrust, 2018], [Interviews Royal HaskoningDHV, 2019-2020]). Leading companies such as the Port of Rotterdam and Royal HaskoningDHV (RHDHV) also use these guidelines to determine the MBL. The two most influential factors for MBL calculations are the draught for which a channel has been designed and the UKC.

As for UKC, there is no international agreement on the UKC build-up and related factors. PIANC provides a build-up of factors to consider when determining an UKC and discusses rough design approaches. However, the results vary widely and are conservative. It is highly dependent on location and situation. Determining an appropriate UKC based on theory is therefore difficult. Based on the previously mentioned and interviews with experts, it is concluded that UKC policies are understandably often based on experience and iteration [Interviews Royal HaskoningDHV, 2019-2020].
Shipping lines and port authorities can have a different perspective on UKC factors to consider and hence policy. Shipping lines sometimes sail with a safer margin than a port imposes on them because they prefer their own for safe navigation. A larger UKC (for safer navigation) is achieved at the expense of cargo. This could be overcome if a port would be more transparent in its design approach and would share real-time data of local and forecasted conditions. This could reduce UKC factor allowances of shipping lines. Shipping lines draw up a loading plan well in advance. If shipping lines can make a better forecast of the local conditions they will encounter, they may load deeper with more confidence. Since vessels, of course, sail internationally and visit multiple ports, an IMO-certificate for a port that guarantees standardised best industry practices for designing channels, acquiring local data and making forecasts, could help the industry move forward. This is a recommendation from this research and is supported by the PoR and Maersk Line.

Navigation channels are designed for a certain draught. When a vessel is fully loaded, the vessel's design draught is reached. Since vessels are not always fully loaded, there is often a difference between a vessel's actual draught and design draught. If a channel is designed for a vessel's design draught, the available water depth is not (always) fully used. Maintenance dredging costs are a large expense for most ports. Actual vessel draughts can help ports with providing insight into what draught should be designed and maintained. Considering actual vessel draughts in the vertical design is a recommendation from this research.

For a location, how is accessibility determined?

If a berth is occupied or if there is too much traffic on a trajectory, a vessel has to wait outside the port (at sea). This is not directly related to the vertical design of channels. Accessibility in terms of available water depth is related to MBL's and water levels (tides). Moreover, for accessibility, a distinction between trajectories with tide-bound and non-tide-bound vessels has to be made. A trajectory is from the sea till berth, or vice versa.

Trajectories with non-tide-bound are designed to allow accessibility at all time (excluding extreme conditions). They can only be limited in case of extreme low water levels or due to strong winds. The latter is especially the case for container vessels; wind forces on containers can become significant and cause the vessel to heel.

For tide-bound vessels, a vertical and/or horizontal tidal window can be in force. With a vertical tidal window, a vessel has to wait for high(er) water levels. In addition, if currents are too strong for a vessel to navigate or manoeuvre safely during a period in the tidal cycle, a horizontal tidal window can be applied.
However, from interviews was concluded that the PoR does not consider these windows separately. These two types of windows are merged into one tidal window. The tidal window is often located at the entrance of a port basin. These tidal windows are based on experience. HCC and pilots know from experience with which currents they can safely manoeuvre into a basin. In fact, they even know which currents they encounter on the rest of their route for a given tidal window. Subsequently, these tidal windows are also chosen in such a way that there is enough water depth available along the trajectory.

3 Maintained Bed Level model

Chapter outline

This chapter sets out to frame a general method to quantify accessibility percentages as a function of the MBL and to develop the required computer model. The following sub-research questions are addressed:

- How can accessibility as a function of the maintained bed level be assessed in a port-network?
    - (a) What approach is required?
    - (b) How can this be modelled?

A new vertical design approach, with a systemic-view, is framed in Section 3.1. The required model outline is considered in Section 3.2. In Section 3.2.5, the required input and data for the model are described. Subsequently, the model's output is addressed in Section 3.2.7. To test the MBL model, a model validation assessment is performed in Section 3.3. Finally, answers to the sub-research questions are provided in Section 3.4.

3.1 Towards a systemic approach

Ultimately, designing MBL's revolves around available and required water depths. In ports influenced by tides and/or river discharge, water levels and hence available water depths vary in time and space. The required water depth varies in space. It is based on a draught for which has been designed, fresh water allowance and local UKC policy. Therefore, a systemic-view of a port-network is required for the vertical design of channels.

3.1.1 Graph (discrete mathematics)

In discrete mathematics, a network is also called a graph. A graph is a structure which consists of a set of objects. Some pairs of these objects are in some sense related. With graph theory, a graph (mathematical structure) is used to model relations between objects. A graph is made up of vertices (also called nodes or points) which are connected by edges (also called links or lines) [Wikipedia, *Graph theory*, 2020]. An example is depicted in Figure 3.1. A vertex is often denoted with a 'V' and an Edge with an 'E'. In this research, a vertex is a location, which is based on a latitude and longitude coordinate ($V_i = V_{x_i,y_i}$). An edge is the connecting-line between two vertices (E_{ij}). This can be considered as a channel. With a graph, a systemic-view of a port can be obtained, and a network (of channels) can be analysed.

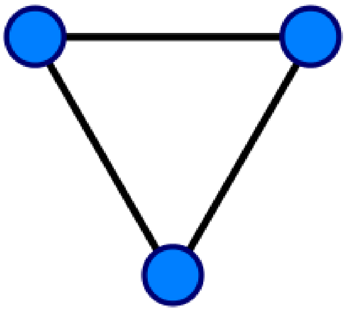


Figure 3.1: A graph with three vertices and three edges

3.1.2 Accessibility at a location (vertex)

In this subsection accessibility at a location, a vertex, is considered. The condition for accessibility is as follows:

$$h_{av}^{\bar{t}} \ \geq \ h_{req} \tag{3.1}$$

Where:

$h_{av}^{\bar{t}}$ = available water depth at time t [m]
h_{req} = required water depth [m]

A formula to calculate the available water depth is presented in Equation 3.2. Formulas to calculate the required water depth are presented in Equation 3.3 and 3.4. One is for a UKC expressed in meters, and the other is for an UKC expressed as a percentage of a vessel's draught.

$$h_{av}^{\bar{t}} \ = MBL_{ref} \ + h_{local,ref}^{\bar{t}} \tag{3.2}$$

Where:

MBL_{ref} = Maintained Bed Level w.r.t. a reference level [m]
$h_{local,ref}^{\bar{t}}$ = local water level w.r.t. a reference level at time t [m]

$$h_{req} \ = T + (T * FWA) + UKC \tag{3.3}$$

Where:

T = the draught for which a channel has been designed [m]
FWA = Fresh Water Allowance (sinkage due to water density difference) [%]
UKC = local Underkeel Clearance policy [m]

$$h_{req} \ = T + (T * FWA) + ((T * FWA) + T) * UKC \tag{3.4}$$

Where:

UKC = local Underkeel Clearance policy [%]

At a location, accessibility should not just be considered as a local water level chance of occurrence. This would exclude the relation between encountered water levels, and tidal windows and vessel speeds. Vessel speeds and the range of a tidal window (if applicable) also influence the available water depths a vessel will encounter on a route. So available water depths should be analysed in relation to a vessel's sailing-plan. If there is no tidal window, water levels in relation to the travel time to a berth can be considered. The previously mentioned is depicted in Figure 3.2.

3.1.3 Accessibility of an edge

Accessibility at a location depends on whether Condition 3.1 is met. However, parameters to determine the required water depth are divided into areas. Water levels are measured at certain locations and with a certain time-step. So there is a network resolution (the distance between vertices). The smaller the network resolution, the more detailed a channel can be designed. This

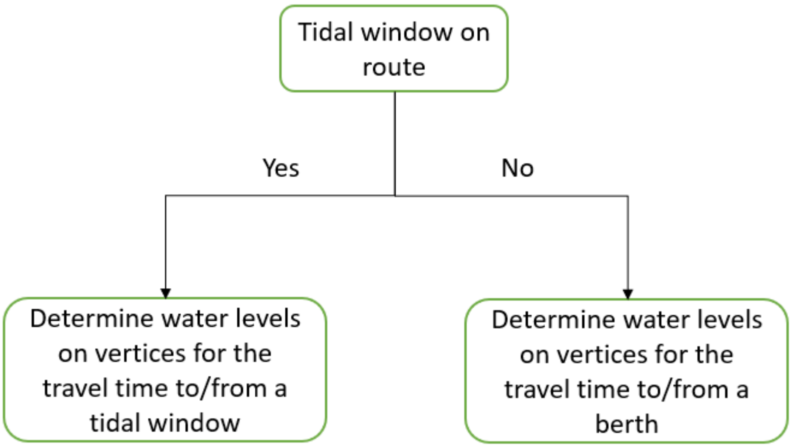


Figure 3.2: Water levels to consider

approach is discrete and not continuous. If a vessel sails in an area, with a certain required water depth, it will encounter an available water depth at the beginning and at the end of the area. For a safe analysis, the smaller water depth of the two must be selected for design purposes. Subsequently, an accessibility analysis can be performed.

The condition for accessibility of an edge is stated below (3.5). By adjusting the MBL, the available water depth changes, and the condition may or may not be met.

$$min(V_i\,|_{h^{\bar{t}}_{av}}, V_j\,|_{h^{\bar{t}}_{av}}) \;\geq\; E_{ij}\,|_{h_{req}} \tag{3.5}$$

As stated before, a distinction between tide-bound and non-tide-bound vessels has to be made for this design approach. When a desired accessibility percentage is determined for a route, MBL's should be adjusted accordingly. Accessibility can be expressed as a percentage of tidal cycles (tide-bound vessels) or time (non-tide-bound vessels).

Tide-bound vessels

For tide-bound vessels, every moment in the tidal window is a 'potential accessibility moment'. If a moment in the tidal window provides accessibility at an edge, this tidal cycle provides accessibility. For a certain MBL and edge, the accessibility is expressed as the percentage of tidal cycles that provide accessibility. As a formula:

$$Accessibility\ (MBL, E_{ij}) = \frac{n_t}{N_t} * 100\% \tag{3.6}$$

Where:

$Accessibility(MBL, E_{ij})$ = Accessibility as a percentage of tidal cycles, for a MBL in an edge [%]
n_t = Nr. of tidal cycles in data-set that provide accessibility in an edge with a MBL
N_t = Total number of tidal cycles in data-set

Non-tide-bound vessels

For non-tide-bound vessels, every moment can be considered as a potential accessibility moment. Hence, accessibility can be expressed as a percentage of time.

$$Accessibility\ (MBL, E_{ij}) = \frac{n_m}{N_m} * 100\% \tag{3.7}$$

Where:

$Accessibility(MBL, E_{ij})$ = Accessibility as a percentage of time, for a MBL in an edge [%]
n_m = Nr. of moments in data-set that provide accessibility in an edge with a MBL
N_m = Total number of accessibility moments in data-set

3.1.4 Conclusion

With this new general method, there can be looped over the MBL to calculate corresponding accessibility percentages. Accessibility percentages can be quantified as a function of the MBL. Subsequently, a MBL corresponding to a desired accessibility percentage can be selected. As a result, it becomes possible to maintain bed levels for neither too little (bottlenecks) nor too much (unnecessary dredging costs) water depth. In order to do so, a computer model would be required. With this systemic-view and model, a port authority could be more rational about where to maintain for which bed level.

3.2 Modelling set-up

3.2.1 Model objective

The MBL model should have a general set up; it should be applicable to ports all over the world. With the general model, available and required water depths can be assessed in a port-network. Subsequently, the bed levels corresponding to a desired accessibility percentage can be selected. Routes to terminals with the largest-draughted vessels should be considered since they determine the required MBL's in channels. Since there are multiple routes in a port, and parameters for calculations vary in time and space, a network must be created. In this network, or graph, properties of vessels and channels have to be assigned to objects to perform calculations.

Historical available water depths (data) along a vessel's route are analysed. So no real-time simulations are performed. Based on the provided data, the model indicates what the accessibility percentages for certain MBL's on a route would have been. For the vertical design, the model must be able to distinguish routes with and without tide-bound vessels. The encountered water levels are different. The model has to determine moments in time when a vessel could have entered or left a port basin (in case of a tidal window) or berth (if no tidal window). So in case of a tidal window, the model must analyse currents. Subsequently, the local water levels a vessel would have encountered on its route can be determined. To calculate at what time a vessel arrives at which location, distances and sailing speeds along the route have to be included. Eventually, available water depths (for varying MBL's) can be compared to required water depths. The model presents accessibility percentages as a function of the MBL. In addition, the MBL's corresponding to a desired accessibility percentage along a route are presented in a side-view plot. Also, the total impact in terms of dredging volumes is provided. There is further elaborated on the output in Section 3.2.7.

Moreover, detailed accessibility figures of berths are presented by the model. These figures are of added value because terminals pay a port authority for the provided MBL at a berth. The port authority subsequently maintains associated channels to the terminal.

With this model, there can be looped over the MBL to calculate corresponding accessibility percentages. Consequently, a port authority can be more rational about where to maintain for which bed level.

3.2.2 Modelling concept

Programming language
The developed model is written in the Python programming language. Jupyter Notebook, from the Anaconda Navigator application, is used as the graphical user interface to write and run the code. The model and related data are available at the GitHub of the TU Delft Hydraulic Engineering department.

Network approach
In the tool, a network of routes can be created by using general latitude and longitude coordinates. These locations are projected in space with the 'pyproj' Python-module. The 'Shapely' - module is subsequently used to link these sections and to create a path. Next, the Python NetworkX-package is used to convert the paths to a NetworkX graph object. This package is designed to research the structure and dynamics of computational networks [Hagberg et al., 2008]. Properties (of vessels and channels), local policies and conditions (data), can be assigned to the network.

Dictionary
Vessels with different types of cargo and destinations (terminal, and in-/outbound), can have a different vessel draught and speed. The draughts and speeds of the largest-draughted vessels handled at the terminals are stored in a dictionary. The user has to insert the destined or departed terminal. Subsequently, the corresponding vessel properties can be called from the dictionary to perform the calculations. Also, the dimensions of channels (edges) are stored in the dictionary.

Dijkstra's algorithm (from NetworkX-package)
With the Dijkstra's algorithm from the NetworkX-package, distances between vertices in the network can be obtained. Subsequently, by calling vessel speeds from the dictionary, it becomes possible to also calculate the durations between vertices. This set-up is used to assess available water depths in time and space along a route.

Time-zones
To handle dates and times in a general way, the 'DateTime' Python-module has been used. Dates and times are converted to a timestamp (number) and stored in a database. A Unix timestamp is the number of seconds between a particular date and January 1, 1970, at UTC.

Methods
A function is a block of code to carry out a specific task. A method in Python is somewhat similar to a function, except it is associated with objects/classes. A method is a function that "belongs to" an object. It can use the data that is contained by an object.

In the proposed MBL design approach, the same relatively simple calculations are made for every vertex and edge; distances and durations, accessibility moments, encountered water levels, comparing available and required water depths, and finally an accessibility quantification as a function of the MBL. By turning these design steps into methods, these calculations can be performed on an entire (complex) network.

3.2.3 Model structure

A vertex is a location in the network. It is based on a latitude and longitude coordinate. So the distances between vertices in the network are not just straight lines; it is really projected into space. The curvature of the earth is taken into account. Subsequently, information (properties and data) can be assigned to vertices and edges. With methods, calculations can be performed all over the network. The outline of the MBL model can be found in Figure 3.3.

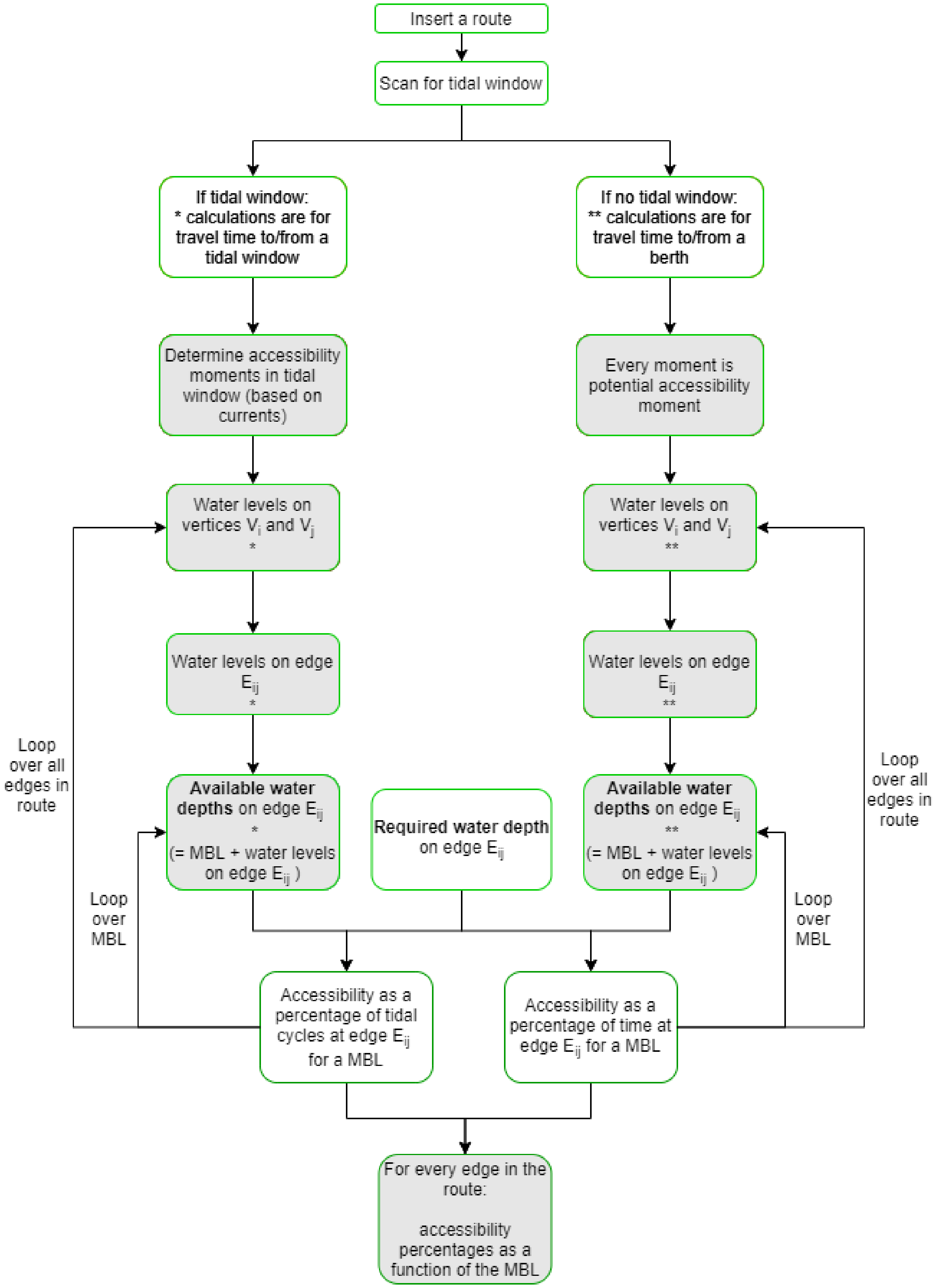


Figure 3.3: Outline of the MBL model; a grey fill denotes a dataframe

3.2.4 Model assumptions

A few simplifications have been made to develop the model. This should be kept in mind while interpreting the results. The following assumptions have been made:

- If there are no local water level data stored at a vertex, the closest data (at another vertex) are assigned to this vertex.
- Local water levels are not continuously stored but with a certain step size. Since they are linked in the model to the time and location of a vessel, the time of a vessel at a location is rounded to the water level step size (to align with this step size).

3.2.5 Model input

Network (coordinates)
In Google Earth, a path can be created by just clicking in the map. By saving such a path from Google Earth as a 'kml'-file and opening it with Notepad, the coordinates are revealed. With these coordinates, a path can subsequently be created in Python (as explained in Section 3.2.2). Because the original paths from Google Earth are made with clicks, the coordinates at path-intersections don't overlap. At these locations, the exact same coordinates at the location of the intersection, have to be added manually to the paths. A linked network is created in this way.
When placing vertices (clicks) to create paths, special attention is given to important positions in the network. A vertex is always placed at a location where:

- Water level data are available
- A tidal window is in force and current-data are available
- Path intersections
- The UKC policy changes
- The fresh water allowance changes

Vessel properties
A vessel's draught is constant along a path, but the speed can vary along a route. Vessel draughts and speeds can depend on whether a vessel is sailing in- or outbound. In- and outbound vessel properties (speeds and draughts) are assigned to edges. These properties are stored in the dictionary and can be called by methods.

Channel properties
Local UKC policies and fresh water allowances are assigned to edges. Moreover, current MBL's are assigned to edges to be able to compare it to the calculated MBL's by the model. In addition, the length of an edge is calculated in the computer model (with the Dijkstra's algorithm), and the width is assigned to an edge. With these parameters, an approximation of the impact in terms of dredging volumes can be made.
MBL's are assigned to edges. Only the berth is an exception. The berth is included as a vertex in the model. It is the first or last point of a route, so it can't be an edge. To be able to calculate dredged cubic meters, the berth length and width are assigned to the vertex. Finally, to get an impression of the lowest water level a vessel encounters during berth, the duration at berth is assigned to the berth-vertex. These properties are stored in the dictionary and can be called by methods.

Data linked to vertices
Local conditions (water levels and currents) data are assigned to vertices in the network. In case of a tidal window, currents and tidal window policies are analysed to determine potential accessibility moments. The resulting potential accessibility moments (data-frames) are linked to the vertices where the tidal window is in effect. For a path without a tidal widow, accessibility moments (every moment) are assigned to berth-vertices.

3.2.6 User input

Accessibility percentage
The user has to insert an accessibility percentage it wants to design for. For example: if the highest potential accessibility is 100%, the user can design for 90% accessibility to assess the impact on the vertical design and dredging volumes.

Route
The user has to insert a route. A route is from sea till berth (inbound) or vice versa (outbound). Based on the berth-vertex, the methods extract vessel properties (draught and speed along the route) from the dictionary.

Loop and plot limits
The user has to insert for which range of MBL's it wants to loop. The MBL step-size can also be inserted. In addition, the MBL limits (y-axis) of the side-view plot can be installed.

3.2.7 Model output

By looping over the MBL in the model, accessibility percentages can be calculated. Per edge (on a route) or vertex (at a berth) with a certain MBL, the current accessibility percentage can be calculated. With a desired percentage to design for, the corresponding MBL can be determined in the model. The proposed and current MBL's along a route are presented in a side-view plot. Also, the total impact in terms of dredging volumes is provided (as a print statement). Moreover, detailed accessibility figures of berths can be presented by the model. The current and proposed accessibility percentages, and corresponding MBL's, are depicted.

3.3 Internal model validation

3.3.1 Internal validation method

The model is tested on four fundamental aspects. First, a route is created in Python (based on latitude and longitude coordinates). If this works, multiple routes can later be combined into a network. Next, basic distance and duration calculations are performed on this route. If this works, the basis for a port-network (systemic-view) on which calculations can be performed has been created. There can be calculated at what time a vessel is at which location (in relation to a tidal window), which could subsequently be linked to a water level in a further application. In the third test, the current data is analysed. The number of tidal-cycles in the data-set is calculated. This is required to be able to link water levels and accessibility moments to a tidal-cycle (in case of a tidal window). Finally, the results of the first, second and third test are used to perform the fourth test; assess encountered water levels along a route in relation to a tidal window. If the model passes these tests, it can be used for further applications; a port-network can be created in which the available and required water depths can be assessed along a route (in relation to a tidal window).
A route to the *3e Petroleumhaven* in the Port of Rotterdam is used for the tests. This is an interesting sample path because a tidal window is in effect at this port basin. In addition, it is a relatively long route over the *Nieuwe Waterweg* (which has recently been deepened) where different water levels will be encountered.

Test 1: Create a path (route) based on coordinates
In Google Earth, the path is created by clicking on the map. By saving the path from Google Earth as a 'kml'-file and opening it with Notepad, the coordinates are revealed. With the longitude and latitude coordinates, the path is subsequently created in Python (as explained in Section 3.2.2). The result is presented in Figure 3.4. The vertices (dots) have been given a number to refer it. The links between the vertices, the orange lines, are the edges. It can be concluded that this aspect of the model functions well.

Figure 3.4: A path to the *3e Petroleumhaven* was created with coordinates

Test 2: Distances and durations
An approximation of the average vessel speeds of the largest inbound vessel-class (15m draught) was used. The speeds are based on HCC questioning and are presented in Table 3.1.

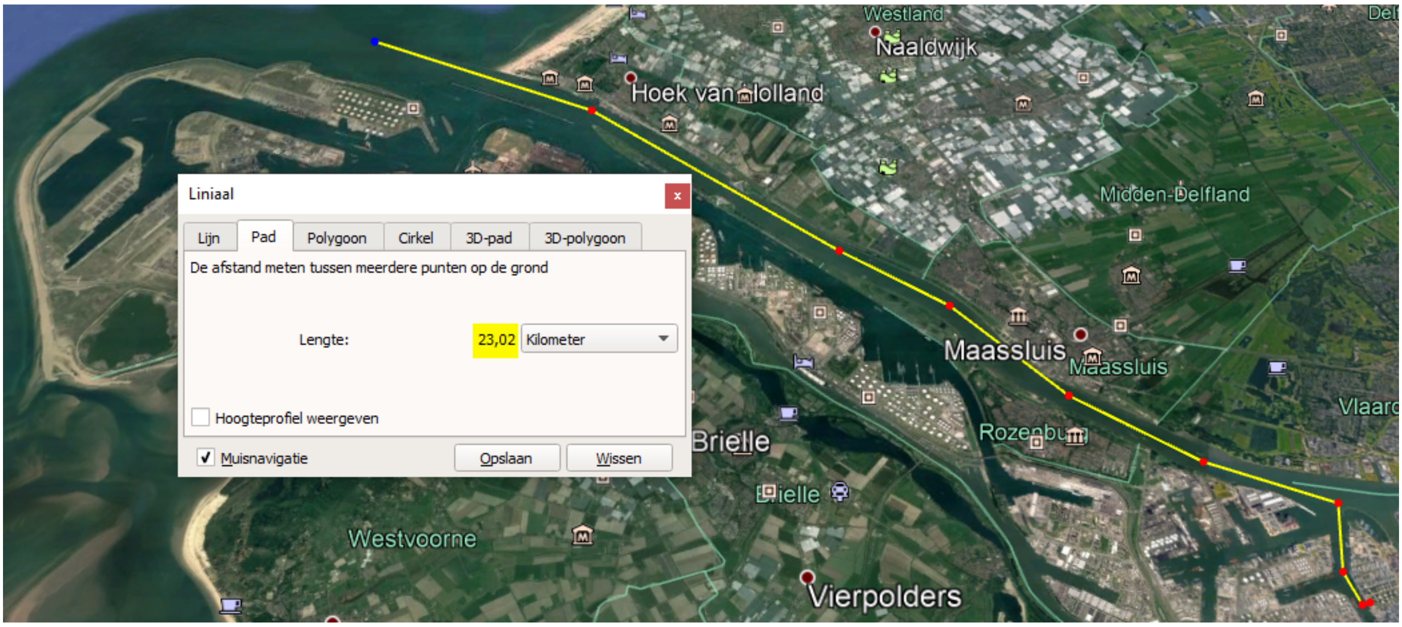
Edge	Approx. average vessel speed [km/hr]
vertex-0_1, vertex-0_5	18
vertex-0_5, vertex-0_9	10
vertex-0_9, vertex-0_11	5
vertex-0_11, vertex-0_13	3

Table 3.1: Average vessel speeds along the *3e Petroleumhaven* trajectory for the largest inbound vessel-class (15m draught)

Subsequently, distances and durations between vertices are calculated in the model. The results are presented in Table 3.2. The total distance (23.02km) as determined by the model is compared to the total distance measured in Google Earth. The distance determined by Google Earth is presented in Figure 3.5. The distances of the model and Google Earth correspond.
With regard to the total duration, the PoR uses 2.5 hours for this route for tidal window calculations [Port of Rotterdam, 2019a]. This duration is from 'pilot on board' till 'first line secured'. The model has calculated 2.2 hours based on estimated sailing speeds. In addition, time to secure lines at the berth is not included in the model's distance and duration calculations. Thus, it can be said that these durations are well matched. Overall, it can be concluded that this test is passed successfully.

Edge	Distance [km]	Duration [s]	Duration [hr]
vertex-0_1, vertex-0_2	5.062	1139	0.32
vertex-0_2, vertex-0_3	3.044	685	0.19
vertex-0_3, vertex-0_4	3.856	868	0.24
vertex-0_4, vertex-0_5	1.72	387	0.11
vertex-0_5, vertex-0_6	2.37	948	0.26
vertex-0_6, vertex-0_7	2.64	1056	0.29
vertex-0_7, vertex-0_8	1.344	538	0.15
vertex-0_8, vertex-0_9	0.76	304	0.08
vertex-0_9, vertex-0_10	0.895	358	0.10
vertex-0_10, vertex-0_11	0.754	905	0.25
vertex-0_11, vertex-0_12	0.431	517	0.14
vertex-0_12, vertex-0_13	0.145	174	0.05
Total	23.021	7878	2.19

Table 3.2: Distances and durations between vertices on the *3e Petroleumhaven* trajectory according to the model



De afstand meten tussen meerdere punten op de grond

Lengte: 23,02 Kilometer

☐ Hoogteprofiel weergeven

☑ Muisnavigatie

Figure 3.5: Total distance *3e Petroleumhaven* trajectory according to Google Earth

Test 3: Number of tidal cycles in data-set

A tidal cycle index has to be created. This is required to link water levels and accessibility moments to a tidal cycle, and subsequently express accessibility as a percentage of tidal cycles. When the direction of the current reverses, a new tidal cycle begins. By performing this analysis on the data-set, it appears that there are 835 tidal cycles in the data-set. In the PoR, there is a semidiurnal tidal constituent, which has a period of 12.42 hours. The data-set contains 430 days. Hence, the astronomical expectation of the number of tidal cycles was 831 (430 * 24 / 12.42). This small difference (4 tidal cycles) is probably due to the rounding-off of the tidal period (12.42 hours). It can be concluded that this test has been passed.

Test 4: Encountered water levels in relation to a tidal window

In this test, a random tidal window that allows access into the port basin is selected (01/01/2019 1:30pm UTC). Subsequently, the encountered water levels along the route are assessed. In order to do so, water level data are assigned to the path. An overview of locations where data are assigned to vertices is presented in Figure 3.6.

For this port basin, the following tidal window is in effect: vessels have to arrive at *Scheurkade* while 0.5kn flood-currents are decreasing. *Scheurkade* is approx. 1.5km in front (observed from sea to berth route) of the port basin. An example of water levels and tidal windows at *Scheurkade* is presented in Figure 3.7. Spatial figures and further elaboration on the accessibility of this port basin are provided in Section 4.4.4.

Figure 3.6: Local water levels (data) are assigned to the path

The encountered water levels are presented in Table 3.3. Average vessel speeds have been applied. As expected (see Figure 3.7), the water levels are decreasing along the route, because the tidal window at the port basin is while flood-currents are decreasing. The total tidal offset for the accessibility moment in this tidal window equals 39 cm (116-77 cm). For design purposes, the PoR takes a tidal offset of 26 cm into account for this route (see Appendix B.3). The tidal offset can differ per tide. The order of magnitude of the model's result and the PoR are the same. As a result, it can be concluded that this test has been successfully completed.

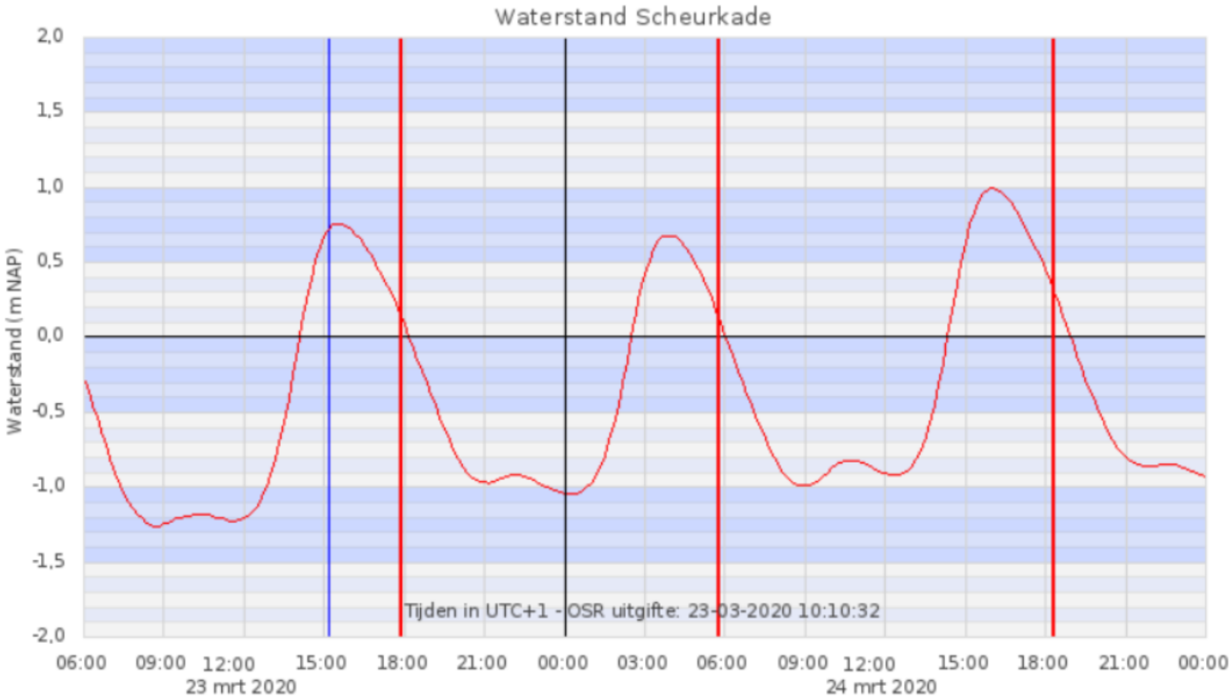


Figure 3.7: Water levels at *Scheurkade*. The red lines indicate accessibility moments (tidal windows) to the *3e Petroleumhaven*

Vertex	Encountered water level [cm wrt NAP]
Vertex-0_1	116
Vertex-0_2	109
Vertex-0_3	109
Vertex-0_4	99
Vertex-0_5	108
Vertex-0_6	99
Vertex-0_7	98
Vertex-0_8	92
Vertex-0_9	92
Vertex-0_10	85
Vertex-0_11	79
Vertex-0_12	77
Vertex-0_13	77

Table 3.3: Model result: encountered water levels for an inbound vessel along its route to the *3e Petroleumhaven*, for a tidal window at *Scheurkade* on 01/01/2019 1:30pm UTC

3.3.2 Conclusion of internal model validation

The model has passed the tests. Hence, the internal validation has been carried out successfully. The model set-up is working as intended. The model provides realistic results for the performed basic calculations. So it can be used for further applications on a more complex port-network (in Chapter 4).

3.4 Conclusion

How can accessibility as a function of the maintained bed level be assessed in a port-network?
(a) What approach is required?

Ultimately, designing MBL's revolves around available and required water depths. In ports influenced by tides and/or river discharge, available water depths can vary in time and space. The required water depth varies in space. Therefore, a systemic-view of a port-network is required for the vertical design of channels.

In discrete mathematics, a network is called a graph. A graph is a structure which consists of a set of objects. With graph theory, a graph (mathematical structure) is used to model relations between objects. With a graph, a systemic-view of a port can be obtained, and a network (of channels) can be analysed. By considering available and required water depths in channels, a method to determine MBL's in a port-network has been framed. By looping over the MBL, corresponding accessibility percentages can be calculated. As a result, it becomes possible to maintain bed levels for neither too little (bottlenecks) nor too much (unnecessary dredging costs) water depth.

This design approach requires: a port-network, vessel- and channel properties, and local conditions data (water levels, and currents in case of a tidal window). A computer model is subsequently needed to quantify accessibility percentages as a function of the MBL.

How can accessibility as a function of the maintained bed level be assessed in a port-network?
(b) How can this be modelled?

The MBL model has a general set up; it can be applied to ports all over the world. In the tool, a network of routes can be created by using general latitude and longitude coordinates. These locations are projected in space with the 'pyproj' Python-module. The 'Shapely' - module is subsequently used to link these sections and to create a path. Next, the Python NetworkX-package is used to convert the paths to a NetworkX graph object. This package is designed to research the structure and dynamics of computational networks [Hagberg et al., 2008]. Properties (of vessels and channels), local policies and conditions (data), can be assigned to the network. With the Dijkstra's algorithm from the NetworkX package, distances and durations within the network can be calculated (geodetic calculations). Moreover, to handle dates and times in a general way, the 'DateTime' Python-module has been used. Dates and times are converted to a timestamp (number) and stored in a database. A Unix timestamp is the number of seconds between a particular date and January 1, 1970, at UTC.

With methods, the same calculations (such as analysing available and required water depths) can be performed on the entire network. The tool scans for tidal windows and determines whether to design for tide-bound vessels or not.

4 Port of Rotterdam case study

Chapter outline

This chapter revolves around performing a traffic (actual draught) study, applying the computer model, and presenting results for the PoR case studies. The following sub-research questions are addressed:

- To what extent can a statement be made, based on traffic data, on how often the available water depth is used?
- What observations can be made for the Port of Rotterdam (case study)?

First, in Section 4.1 cases are selected to be studied. Subsequently, the associated network of channels was created in Section 4.2. An actual draught traffic study is carried out in Section 4.3. Next, in Section 4.4, all values of the model parameters (input) are discussed. Results from the model are presented in Section 4.5. The model was run for current channel design parameters. Also, to provide insight, runs with alternative vessel draughts (input), based on the traffic studies, have been presented.

Moreover, terminals pay the PoR for the facilitated MBL at a berth, the price increases for every 10cm extra depth. The PoR and RWS subsequently maintain the associated waterways. Therefore, detailed berth accessibility figures are also included in the results. They are of extra added value (compared to other parts of channels on the route) to present to a terminal. Subsequently, in Section 4.6, a sensitivity analysis was performed on various parameters to gain insight into how strongly they influence the vertical design. Ultimately, answers are provided to sub-research questions in Section 4.7.

4.1 Terminal comparison

The selected cases (terminals) should be handling the largest-draughted vessels, because these vessels determine the required MBL's of channels. Such a vessel is 'normative' for (a certain part of) a route. Moreover, different kinds of interests, wishes and economic dynamics revolve around different types of cargo. Therefore, it would be interesting to consider different types of terminals. The discrepancy's between actual draught and design draught may vary per terminal. In addition, there is a hypothesis that the oldest parts of the port have had the least recent MBL consideration. This is in the city centre of Rotterdam (the origin of the port), this part of the port is called 'city'.

Criteria for cases:

- Terminal should be handling 'normative' (largest-draughted) vessels in channels
- Different types of cargo
- Consider one older part of the port

Based on these criteria, the following cases have been chosen:

- Liquid bulk: Koole terminal, *3e Petroleumhaven*
- City: Uniport terminal, *Waalhaven*
- Dry bulk: EMO terminal, *Mississippihaven*

- Container: APM terminal, *Prinses Amaliahaven*

Figure 4.1 presents an overview of the routes to the considered terminals. The black line is a route to the *2e Petroleumhaven*. The channels on this route are deepened to handle larger-draughted vessels (15m) in the near future, but these vessels are not handled there yet.

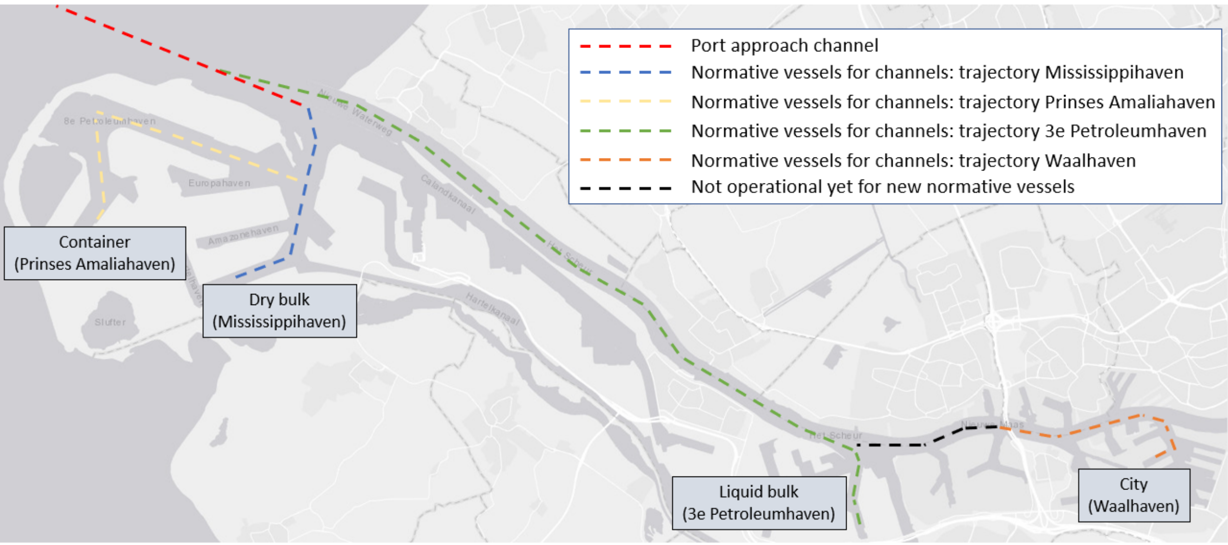


Figure 4.1: Normative vessels in channels to the considered terminals (cases)

4.2 Network

As explained in Chapter 3, a network has been created to be able to analyse MBL's over routes. Four paths to the relevant terminals were created in Google Earth, the latitude and longitude coordinates were copied to Python and were manually merged to create a network. The result of this network, which has subsequently been opened with Google Earth again, is presented in Figure 4.2.

Figure 4.2: A port-network was created by using latitude and longitude coordinates

Every vertex (a dot in Figure 4.2) in the network has been given a name to be able to refer to it in the model. These vertex-names are presented in Appendix C. The link between two dots, the orange lines, are the edges.

4.3 Traffic study (actual draughts)

As explained in Chapter 2, channels are designed for a certain draught. This section sets out to provide insight into how actual draughts relate to draughts for which channels have been designed. In addition, the underlying (economical) reasons for discrepancy's are described.

The traffic data ranges from January 2015 through February 2020 and was obtained from HaMis. Vessels' design draughts are provided in the data-set. This is not the scantling or another type of draught.

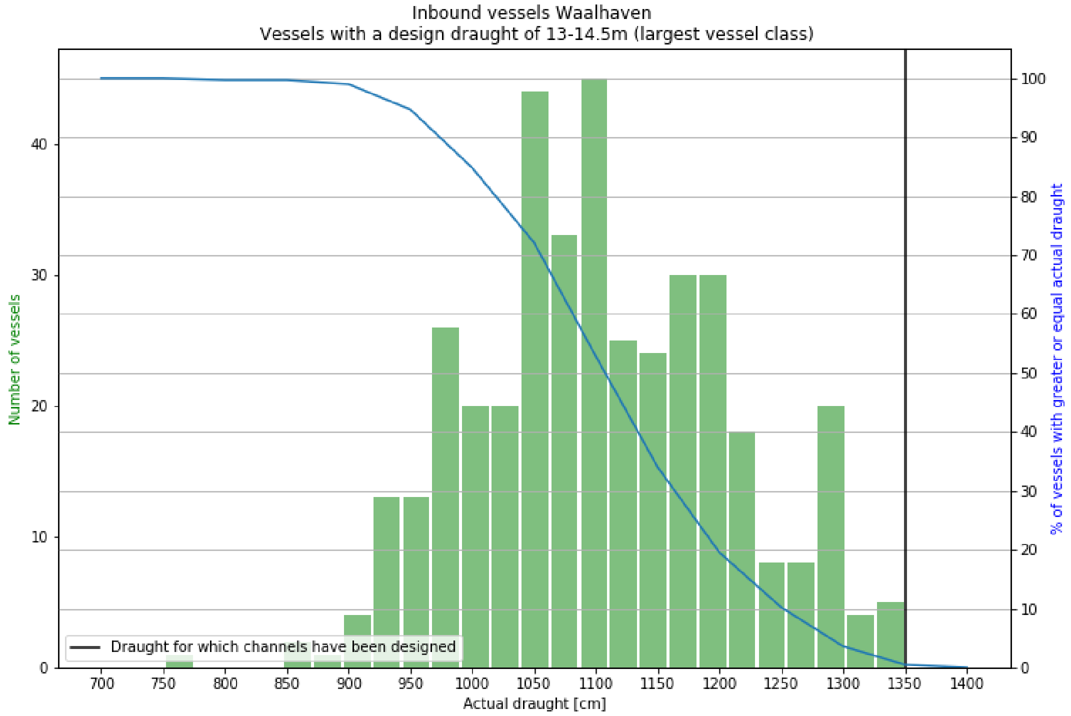
4.3.1 Liquid bulk terminal

The draught of liquid bulk tankers to the *3e Petroleumhaven* is limited by the depth on the *Nieuwe Waterweg*. This channel has recently been deepened (April 2019) to allow vessels with a draught of 15m. The design draught of these vessels is 17m, but the channel cannot be deepened further due to the national interest in limiting salt intrusion [Interviews Port of Rotterdam, 2019-2020]. In addition, the depth is limited by the concrete foundation of the *Maeslantkering* (storm surge barrier) [Interviews Port of Rotterdam, 2019-2020]. As a consequence, vessels are generally loaded to their maximum allowable draught (15m). Only a few vessels have visited the *3e Petroleumhaven* with this draught yet. An actual vessel draught distribution figure is therefore not presented in this section. For completeness, it can be found in Appendix D.

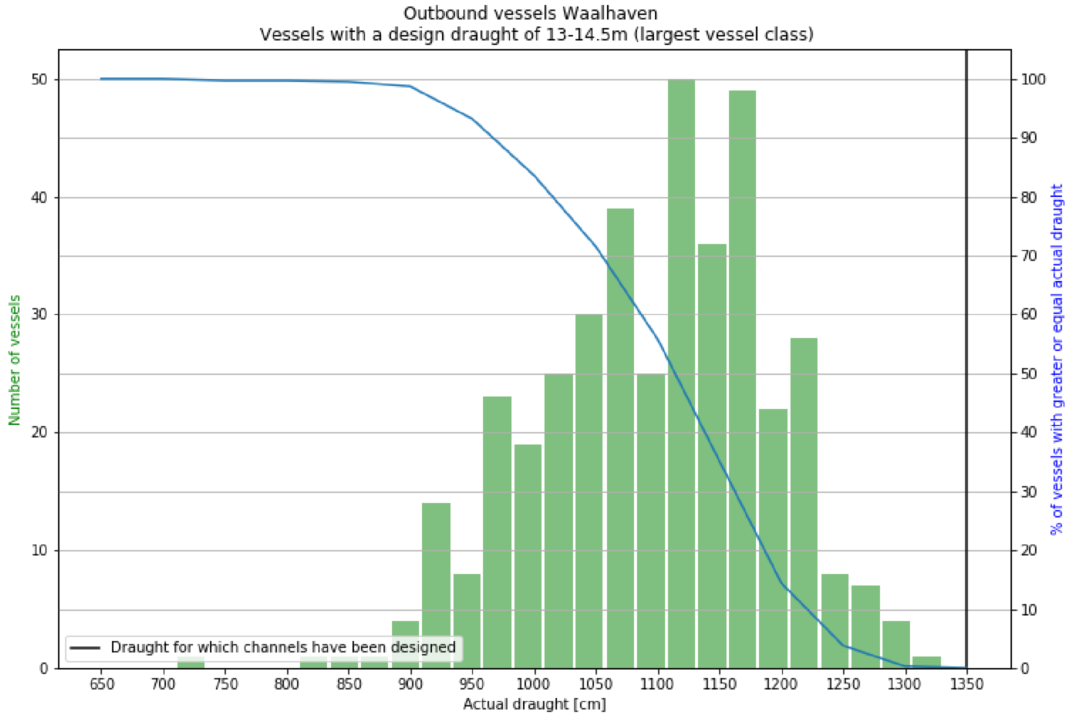
4.3.2 'City' terminal

The MBL's in channels to the *Waalhaven* have been designed to allow vessels with a draught of 13.5m. Varying types of cargo are handled in the Waalhaven, but container vessels sail with the largest draughts in this port basin. The largest actual draught that has been reached since 2019 is half a meter (13.0m) below the draught for which the channels have been designed (13.5m). In 2016 and 2018, an actual draught of 13.5m has only been reached once. The largest actual draught that was reached in 2017 was 12.9m. To provide insight into potential benefits, an alternative draught of 13.0m will also be analysed in the model.

In Figure 4.3, actual vessel draught distributions have been presented of the largest-draughted vessel classes (13 - 14.5m) handled in the *Waalhaven*. Less than 17% of these container vessels (in- and outbound combined) achieve an actual draught of 12m. The draught for which channels have been designed (13.5m) is achieved by only 0.5% of the inbound vessels and by none of the outbound vessels.



(a) Inbound vessels Uniport terminal



(b) Outbound vessels Uniport terminal

Figure 4.3: Actual vessel draught distribution of largest in- and outbound container vessels Waalhaven (data from HaMIS: January 2015 - February 2020)

4.3.3 Dry bulk terminal

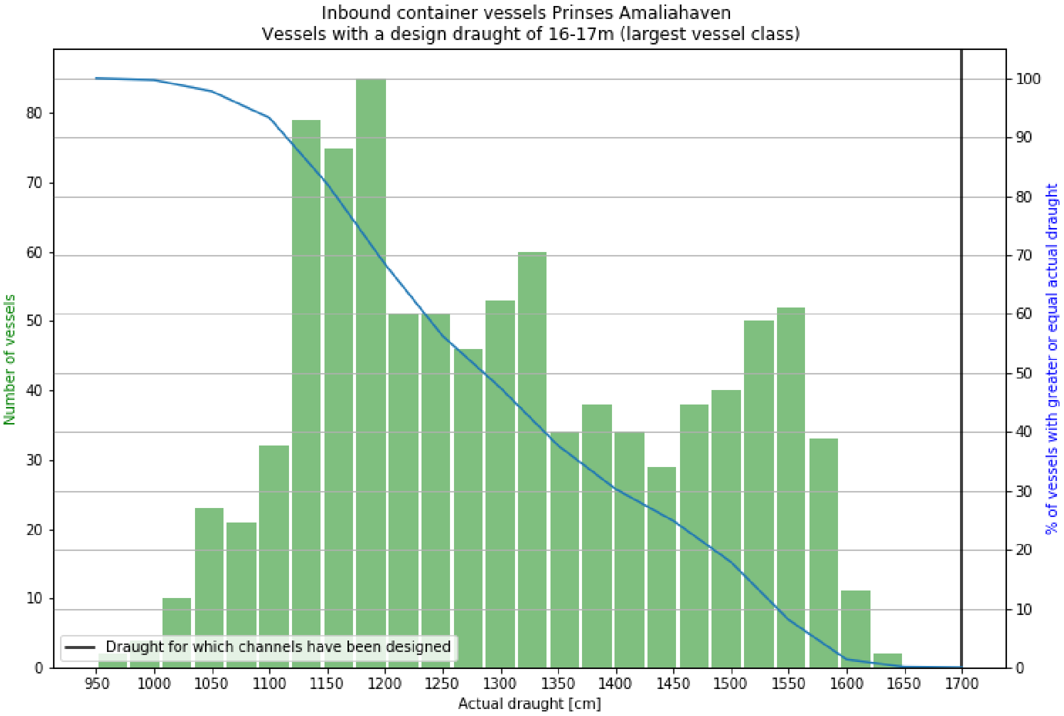
The MBL's in channels to the *Mississippihaven* have been designed to allow vessels with a draught of 22.6m. This was designed as such in a time when China placed a trade restriction on Brazil [Interviews Port of Rotterdam, 2019-2020]. These vessels came to the PoR instead of China during this trade restriction. Since 2016, this restriction has been lifted, and these vessels are sailing directly from Brazil to China again. The traffic data showed that the draught for which the channels have been designed (22.6m) was last (almost) reached in January 2016. The largest actual draught that has been reached since May 2016 is approximately 4m below the design draught (18.6m). The traffic data does not reveal more relevant insights, but for completeness, actual vessel draught distributions can be found in Appendix D.

4.3.4 Container terminal

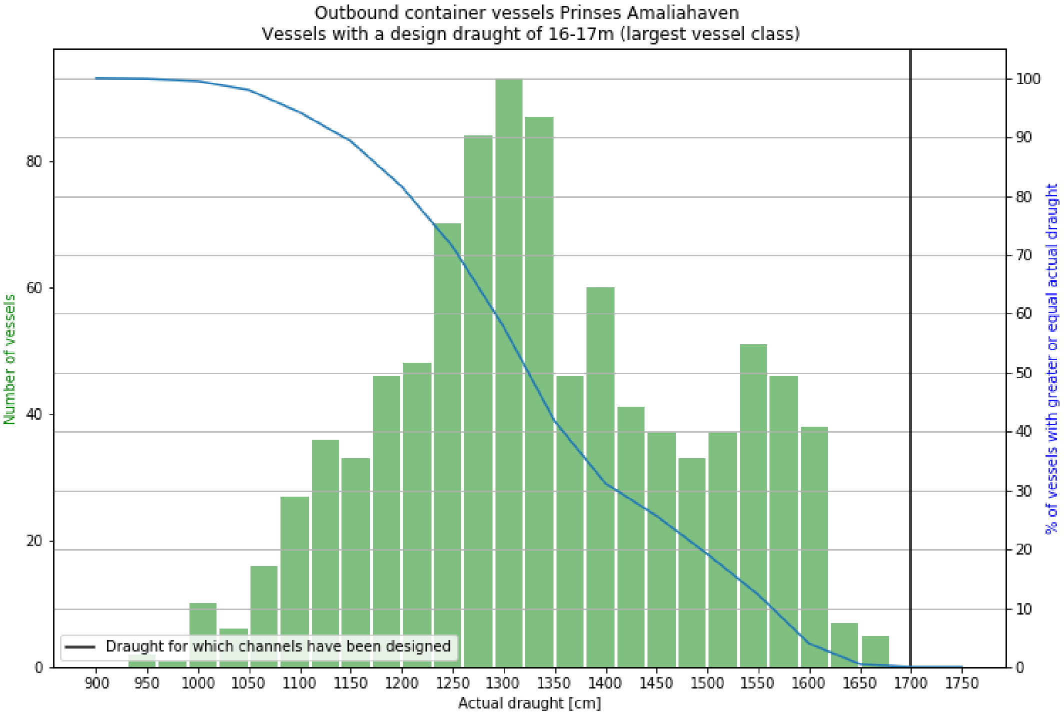
Container vessels are scheduled services and have a tight schedule [Interviews Port of Rotterdam, 2019-2020], which is why the route is designed to have no tidal window. The fast increase in vessel sizes is remarkable in the container business. The carrying capacity has increased with approx. 1200 % since 1968 [Marine Insight, 2019], to reduce the costs per container.

In Figure 4.4, actual vessel draught distributions have been presented for the largest vessel classes (16-17m design draught) handled at the *Prinses Amaliahaven*. It becomes clear that these vessels are very rarely fully loaded and seldomly (almost) reach their maximum (design) draught. Only 0.5% of vessels (in- and outbound combined) reach an actual draught of 16.5m, while the draught for which channels have been designed equals 17m. In addition, less than 20% of these container vessels achieve an actual draught of 15m. However, the *Prinses Amaliahaven* was built for the future. Recently, an actual draught record of 17.3m was achieved [Port of Rotterdam, 2020b]. This is not included in the data.

Moreover, to provide 99% of the time accessibility, channels can be designed on the 99.5% largest actual draughts, as 99% multiplied by 99.5% still results in 99 % of the time accessibility for a random vessel calling at this terminal. Then there could be designed with 16.5m draught instead of 17m. Although the terminal is designed for the future, this alternative draught will be analysed in the model to provide insight into the benefits in terms of dredging volumes.



(a) Inbound vessels APM terminal



(b) Outbound vessels APM terminal

Figure 4.4: Actual vessel draught distribution of largest in- and outbound container vessels Prinses Amaliahaven (data from HaMIS: January 2015 - February 2020)

4.4 Input

This sections sets out to provide an overview of the input that has been used in the model. It discusses and explains the establishing of the applied parameters for the cases.

4.4.1 Vessel draughts

Draughts for which channels on the trajectories of the four terminals have been designed are obtained from the Port of Rotterdam: DHMR [2019]. The largest observed actual draughts, and interesting alternative actual vessel draughts, were found in Section 4.3. These draughts are presented in Table 4.1. There are no outbound vessel draughts defined by the PoR for which channels have been designed.

Port basin	Draught for which channels have been designed [cm]	Largest inbound actual vessel draught [cm]	Largest outbound actual vessel draught [cm]	Alternative (actual) vessel draught to design for [cm]
3e Petroleumhaven	1500	1500	1270	n/a
Waalhaven	1350	1350	1330	1300
Mississippihaven	2260	2230	1840	1860
Prinses Amaliahaven	1700	1650	1680	1650

Table 4.1: Overview of draughts

4.4.2 Vessel speeds

The PoR has been storing moments, using AIS signals transmitted by vessels, when vessels pass a certain line in the port. Figure 4.5 presents an overview of these lines. More detailed figures of these lines are provided in Appendix E.2.1.

With the help of AIS data, it becomes possible to determine exactly at what time a vessel is sailing at which location in the port. Based on time and distance, vessel speeds can be calculated along a vessel's route. Vessel speeds relative to the water, which differ due to the tide and river discharge, do not have to be included with this approach. With the vessel speeds, it becomes known at what time a vessel is at which location. Subsequently, it can be linked to a local water level in the model.

The results of the inbound and outbound vessel speeds on the trajectories of the four terminals are presented in Table 4.2. There are often no counting lines at the berth site. For this first or last part of the route, a speed of 3 km/h has been assumed (based on HCC questioning). Vertices and counting lines do not always coincide exactly. In that case, the speed between two counting lines in which an edge finds itself has been used. Full calculations have been presented in Appendix E.2.2. For the analyses in the model, average vessel speeds are applied. In Section 4.6, a sensitivity analysis is performed on this parameter.

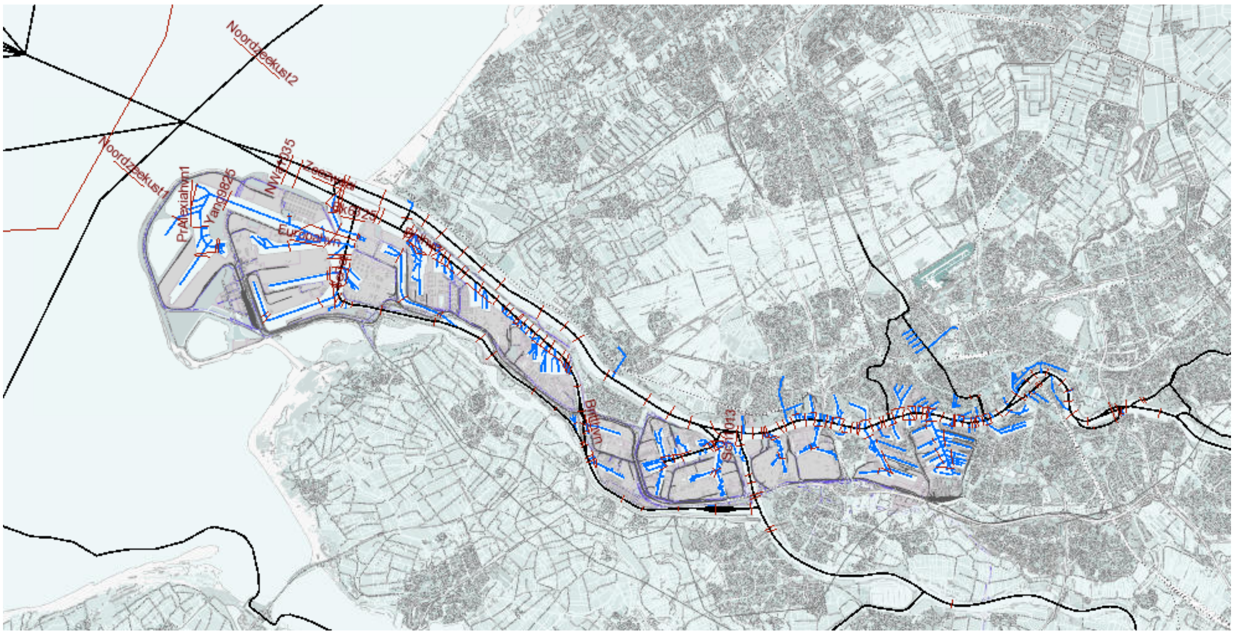


Figure 4.5: Passing lines for which AIS data are recorded in the PoR

	Inbound vessel speed [km/h]			Outbound vessel speed [km/h]		
	$v_{minimum}$	$v_{average}$	$v_{maximum}$	$v_{minimum}$	$v_{average}$	$v_{maximum}$
Basin						
3e Petroleumhaven	4	4	4	5	7	8
Waalhaven	11	14	17	17	17	17
Mississippihaven	6	11	13	9	10	13
Prinses Amaliahaven	6	7	8	4	5	6
Fairway						
3e Petroleumhaven	14	16	17	19	21	23
Waalhaven (NWA1035-Sch1021)	13	16	19	14	18	21
Waalhaven (Sch1021-NMA1005)	12	13	15	12	13	13
Mississippihaven	8	9	10	7	10	12
Pr.Am. (Calandkanaal-Beerkanaal)	11	13	15	12	13	15
Pr.Am. (Beerkanaal-Yangtzeekanaal)	8	9	10	5	8	9
Approach channel						
3e Petroleumhaven	13	16	18	24	26	28
Waalhaven	17	21	24	21	24	28
Mississippihaven	13	14	16	16	19	20
Prinses Amaliahaven	11	17	21	22	22	23

Table 4.2: Vessel speeds of the largest vessel classes on trajectories of the four terminals

4.4.3 Local conditions (water levels & currents)

To calculate available water depths along a route, local water levels are assigned to vertices in the network. In addition, to determine the accessibility of a channel with respect to a tidal window, currents are assigned to vertices where a tidal window is in effect. This includes rates and directions. Subsequently, the available water depths along a route in relation to a tidal window (if applicable) can be calculated. The data are extracted from OSR by the PoR and ranges from 01-01-2019 through 05-03-2020 (429 days). An overview of locations where data are assigned to vertices is presented in Figure 4.6. The names and characteristics of these measurement-points, as used in the model, are presented in Appendix E.1.

(a) Local water levels

(b) Local currents

Figure 4.6: Local conditions (data) are assigned to vertices in the network

4.4.4 Port basin accessibility

As described in Section 2.3.2, guidelines for accessibility are stored by the PoR in a document: "Port of Rotterdam: DHMR & HCC [2020]". These guidelines are used in the computer model. Only the accessibility restrictions of the largest-draughted vessels are applied and discussed.

The wet infrastructure in Rotterdam is designed to provide accessibility with 99% of the tidal cycles (often during high tides) for tide-bound vessels and 99% of the time for non-tide-bound vessels. High accessibility is of economic importance. There was chosen for 99% instead of 100 % to not design for rare extreme low water levels.

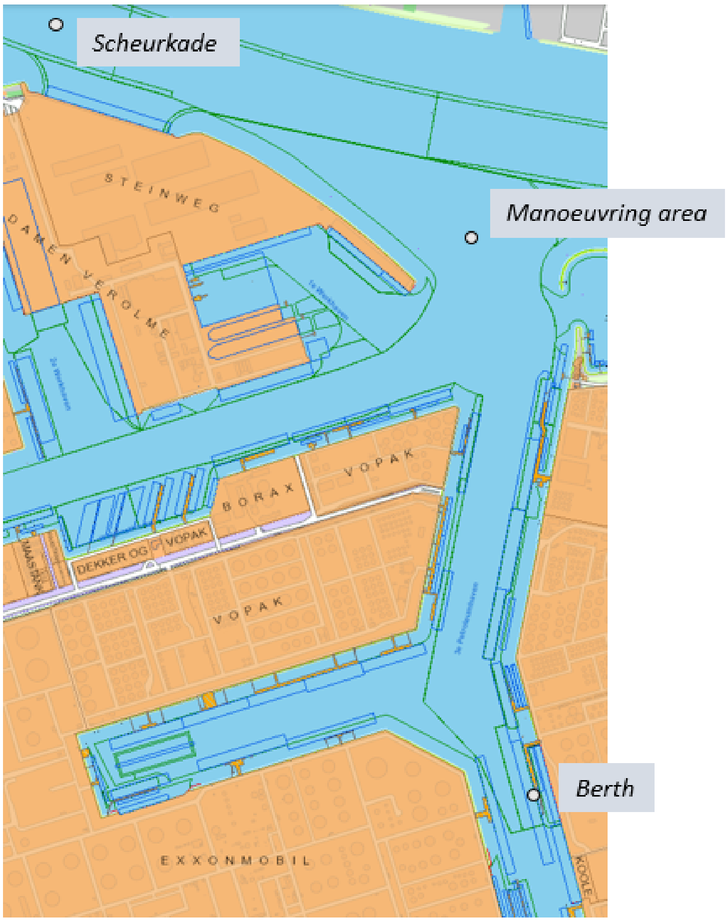
Only the tidal window for the *3e Petroleumhaven* is a point-based tidal window. There is a specific moment in the tidal cycle when vessels have to arrive at the port basin. The other cases have an accessibility window. This will be explained further in the section below. An interesting observation was made; only 99.04% of the tidal cycles (of the past 429 days) provide this specific accessibility moment for the *3e Petroleumhaven*. So based on these currents, not every tidal cycle has the potential to provide accessibility. To subsequently not design for extreme low water levels, 1% is deducted (as does the PoR). Hence, the desired accessibility to design for becomes 98.04%. For the other cases, each tidal cycle offers a potential accessibility moment, and is designed for 99% accessibility.

3e Petroleumhaven

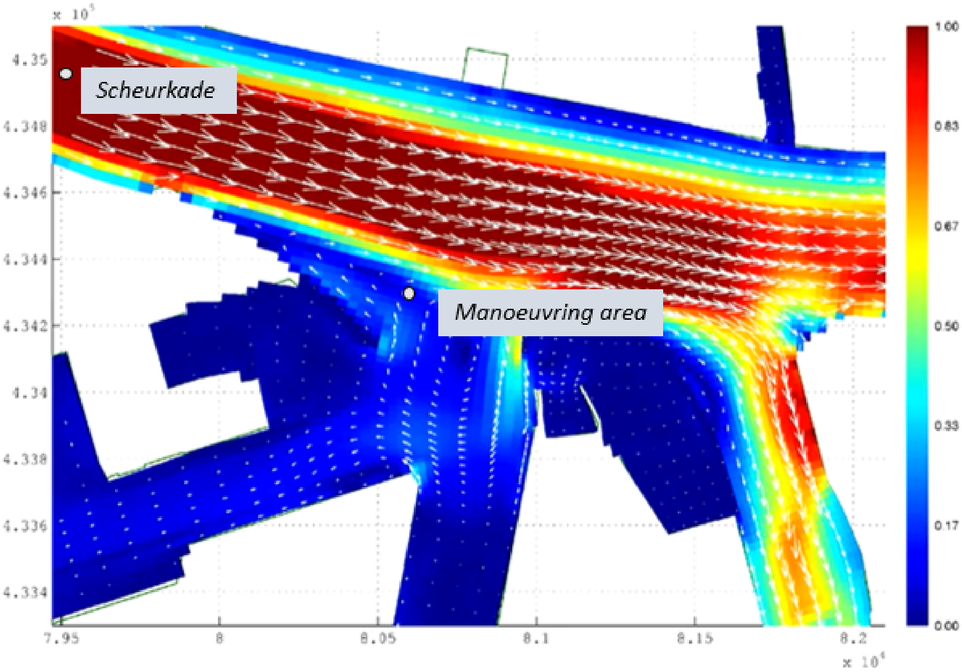
For this port basin, the following tidal window is in effect: vessels have to arrive at *Scheurkade* while 0.5kn flood-currents are decreasing. *Scheurkade* is approx. 1.5km in front (observed from sea to berth route) of the port basin. This is a great example of an experience-based tidal window. Pilots know that with this tidal stream rate, they will have the correct stream rate (approx. zero) to manoeuvre into the port basin as soon as they arrive there. In fact, they even know that at the beginning of their route at *Hoek van Holland* (16 km away), they will not be bothered too much by currents [Interviews Port of Rotterdam, 2019-2020].

So this is a point-based accessibility moment according to the guidelines. However, local conditions are measured and predicted every 10 minutes. So a vessel very rarely arrives at exactly 0.5 kn. In practice, there is a window around this point-based tidal window. Based on interviews with HCC [Interviews Port of Rotterdam, 2019-2020], this window is approx. ± 30%, and is used as such in the model. For outbound vessels, the same tidal window is in effect.

Figure 4.7 depicts locations which are relevant for the accessibility of this port basin.



(a) Port basin



(b) Example local currents (m/s) (from OSR: 18-Aug-2020 15:50 UTC+2)

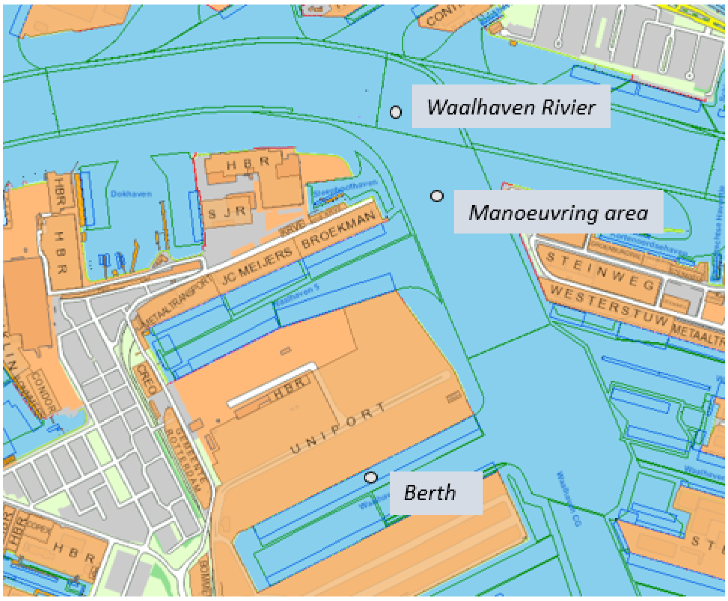
Figure 4.7: Important locations for accessibility of the *3e Petroleumhaven*

Waalhaven

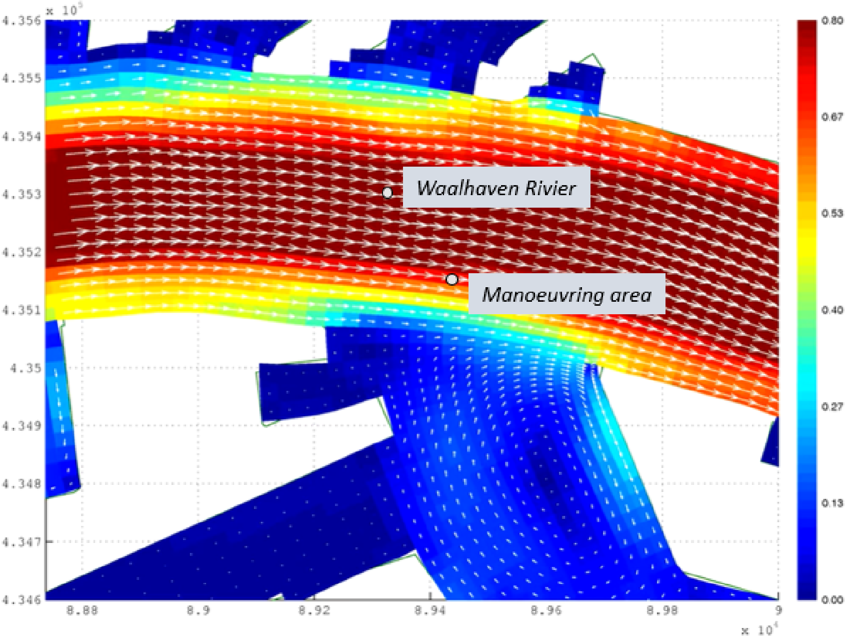
The largest-draughted vessels in the Waalhaven are container vessels. They can arrive at the *Waalhaven Rivier*, while:

- Inbound vessels: max flood-currents equals 0.7kn and max ebb-currents 0.7kn
- Outbound vessels: max flood-currents equals 0.5kn and max ebb-currents 0.5kn

Figure 4.8 depicts locations which are relevant for the accessibility of this port basin.



(a) Port basin



(b) Example local currents (m/s) (from OSR: 18-Aug-2020 3:40 UTC+2)

Figure 4.8: Important locations for accessibility of the *Waalhaven*

Mississippihaven

There is also a tidal window for the largest-draughted vessels in the *Mississippihaven*. The manoeuvring area in front of this port basin is called *Beergat*. Vessels are influenced by lateral currents coming from the channel to the right of *Beergat* (*Hartelkanaal*). The follow tide restrictions are in effect:

- For inbound vessels: only high tide at *Beergat* is allowed
- For outbound vessels: slack water at *Beergat* is required

Figure 4.9 depicts locations which are relevant for the accessibility of this port basin.

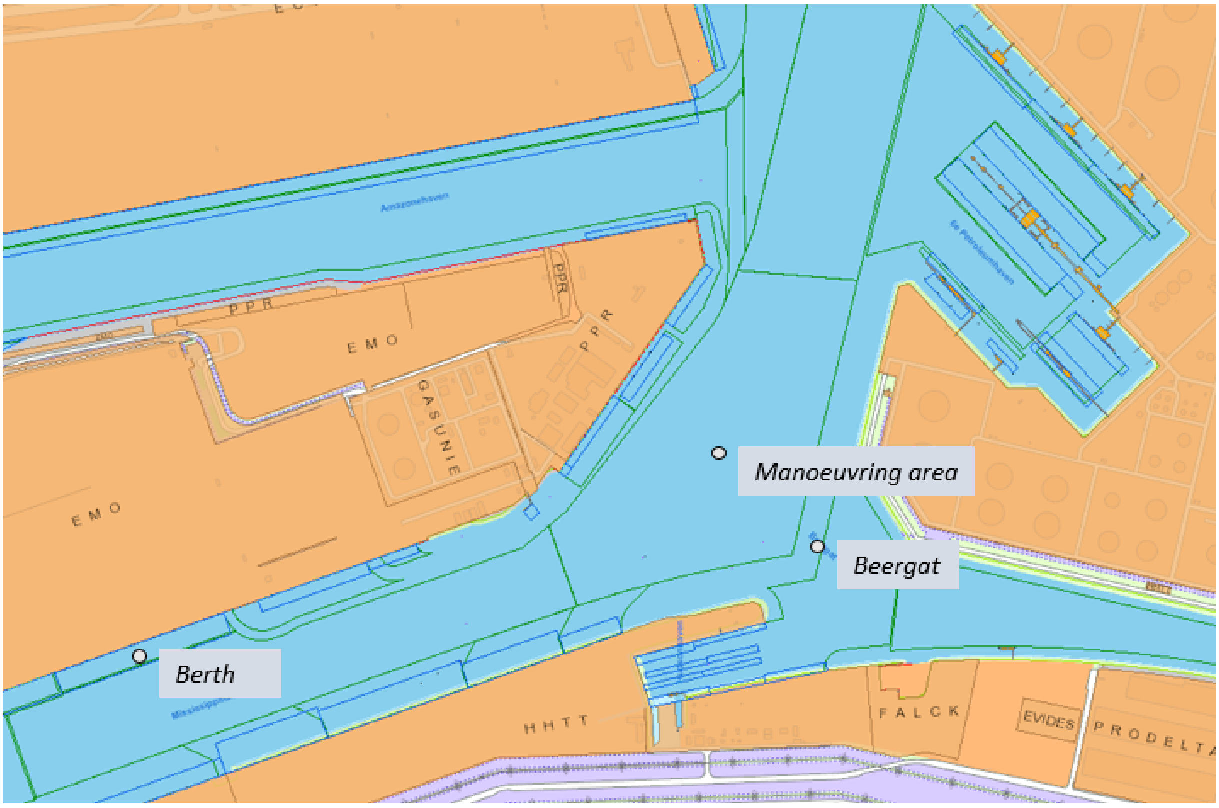


Figure 4.9: Important locations for accessibility of the *Mississippihaven*

Prinses Amaliahaven

This is the only case without a tidal window. These container vessels have tight schedules and require 99% of the time accessibility. As for depth, they can only be limited in the case of extreme low waters. In addition, accessibility can be limited by wind speeds, but they do not affect MBL design. Every moment is therefore a potential accessibility moment. Since the data of local water levels are in steps of 10-minutes, an accessibility analysis can be performed every 10 minutes.

4.4.5 UKC & FWA

Underkeel clearance policies and fresh water allowances (sinkage due to water density differences) have been assigned to edges in the network. The UKC policy as imposed by the PoR has been used, this policy is presented in Appendix B.4. In addition, the areas indicated by the PoR with a fresh water allowance of 1% or 2.5% of a vessel's draught have been used. These areas are presented in Appendix B.2. Water densities in channels vary all the time due to tides. The FWA margin is a maximum safe allowance (worst case scenario).

4.4.6 Channel dimensions

The channel dimensions are needed to express the consequences of adjusting the MBL in terms of volumes of dredged material. The length, width and current MBL are assigned to edges and berths in the model. The length of edges are obtained from the network by using a 'distance over path' method that was written in Python. The PoR has divided channels into maintenance areas. This is depicted in Figure 4.10. The surface areas are known. Subsequently, the width of edges can be calculated by using the known surface areas and lengths. The results have been checked with manual measurements in port maps. Finally, the current MBL's have also been added to the network. This allows the proposed MBL's to be compared to current MBL's. For berths, the length and width are based on the surface area of the maintenance areas. The values of the channel dimensions are presented in Appendix E.3.

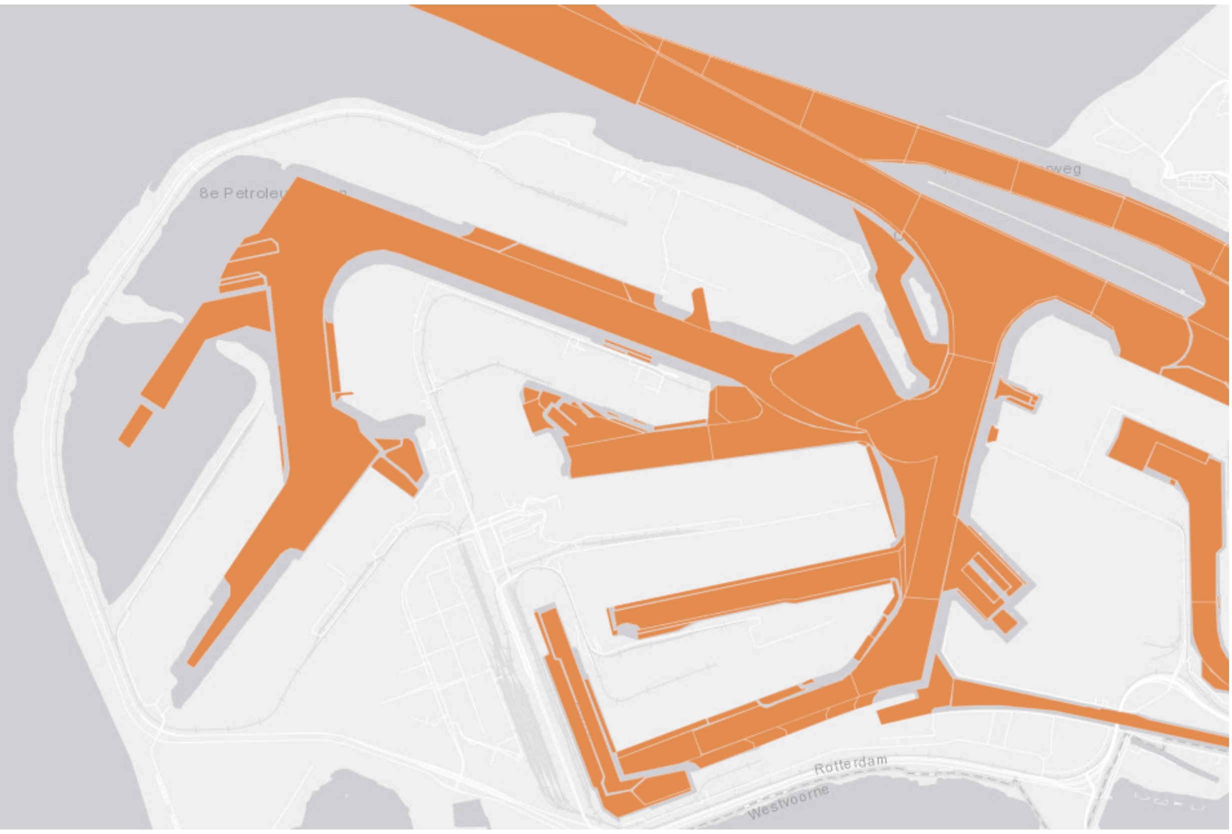


Figure 4.10: Example of maintenance areas in the *Maasvlakte* PoR

4.4.7 Duration at berth

While a vessel is at berth, it encounters varying water levels due to tidal variations. A berth pocket is designed for low water levels to make sure a vessel does not hit the bed. For all arrival times at berth, the model determines the lowest water level that occurs for a given duration while a vessel is moored. Subsequently, it calculates accessibility percentages as a function of the MBL. Therefore, the duration at the berth of the largest-draughted vessels has been analysed. Traffic data (from HaMis) was used to provide this insight. The result is presented in Table 4.3. Full calculations have been presented in Appendix E.4.

For design purposes, the maximum duration at berth should be applied. However, if vessels are moored for a relatively short duration in the future (due to operational developments), the tidal window may influence the encountered low water level at berth. This is an example of a systemic view that the model can include. For the sake of completeness, this has been added to the model.

	Berth duration for vessels with a draught for which channels have been designed [days]		
	Minimum	*Average*	*Maximum*
Port basin			
3e Petroleumhaven	3.0	5.8	7.2
Waalhaven	0.7	1.1	1.4
Mississippihaven	4.2	5.8	7.2
Prinses Amaliahaven	1.6	1.8	2.4

Table 4.3: Duration at berth for largest handled vessel classes

4.5 Case studies

Results from the model are presented in this section. First, a run is performed for each case with the draught for which channels have been designed. This is an analysis of the MBL's and related accessibility percentages of existing channels. A side-view plot with current and suggested MBL's for an in- and/or outbound vessels along a route are presented. The normative trajectories, as presented in Figure 4.1, are analysed. A spatial image with km notation is included to support the side-view plots. In addition, a detailed berth accessibility figure is provided. Such a figure could be made for every edge. The berth is chosen because terminals pay for this facilitated MBL. In addition, an analysis with an alternative (actual) vessel draught, as was presented in Table 4.1, is performed for every case. Furthermore, a potential bottleneck at the *Maeslantkering* is investigated for the *3e Petroleumhaven* trajectory.

4.5.1 Liquid bulk terminal

Output for current channel design

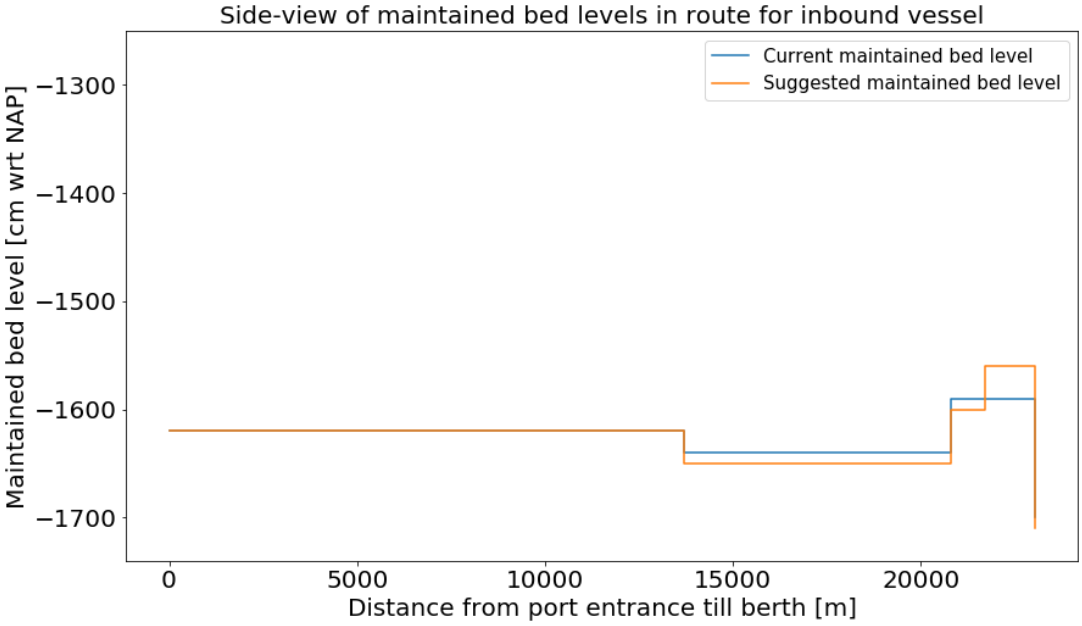
Equation 2.3 has been invented and applied for the recent deepening of the *Nieuwe Waterweg*. The MBL's on this route have therefore recently been carefully considered. This case is therefore a perfect case to test the results of the computer model.

On the *Nieuwe Waterweg*, the model only suggests 10cm extra MBL for the last part (approx. km notation 14-21km). The current accessibility of this part of the route equals 94.85% and is a bottleneck. By dredging only 10cm extra MBL, the accessibility becomes 98%. Furthermore, the proposed MBL on the *Nieuwe Waterweg* fully corresponds to the recent (current) deepening. The small suggested deepening (10cm) just after the 20km notation is at the port basin manoeuvring area. Inside the port basin, there may be 30cm less MBL according to the model. This has been discussed with a pilot sailing this route with these vessels (Interviews others [2019-2020]). From his experience, sailing into this port basin "feels like putting a cork back into a wine bottle". Water is pushed out of the basin by sailing through the confined channels, especially when more vessels are moored. The return flow negatively influences the controllability of the vessel. Less MBL, as suggested by the model, is therefore not recommended. This is an effect that is not included in the UKC build-up and policy. Theoretically, there may be 30cm less MBL, but apparently, this extra water depth is needed for safe navigation in the confined channels. Therefore, extra MBL is facilitated. Adjusting the UKC policy for confined channels (to 80cm instead of 50cm in this case) would be recommended.

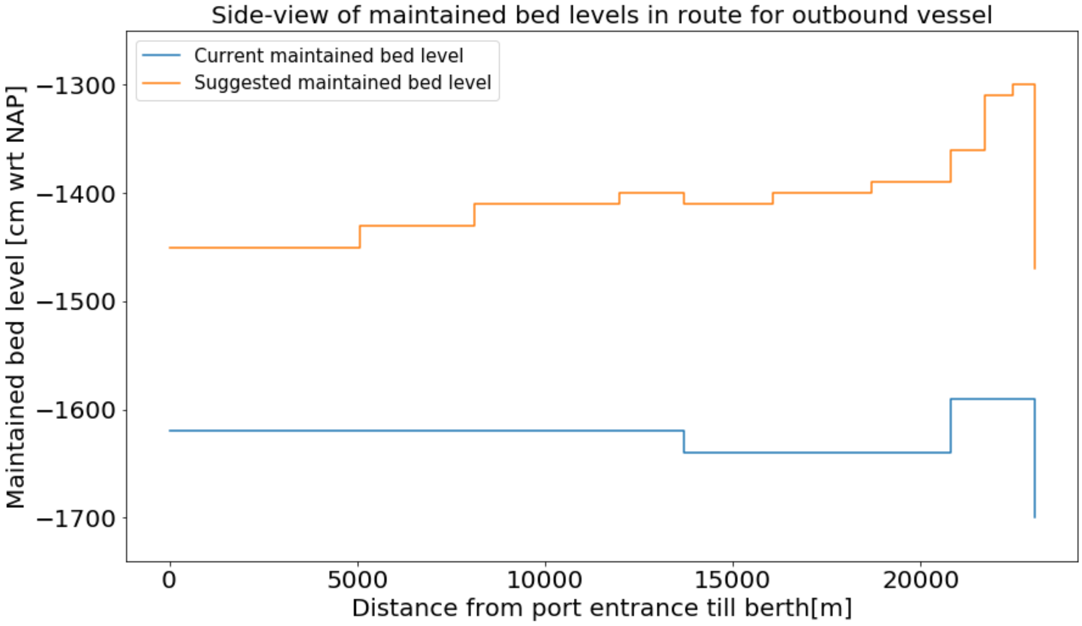
At berth, the model suggests 10cm more MBL. Figure 4.13 presents detailed accessibility percentages as a function of the MBL for the berth. The accessibility with 98.04% of the tidal cycles will be in accordance with the accessibility of the trajectory.

Figure 4.11: Spatial image with km notation for *3e Petroleumhaven* trajectory (from port entrance till berth)

For outbound vessels, the smallest difference between the suggested and current MBL is at the beginning of the *Nieuwe Waterweg* (approx. km notation 0-5km). From an analysis with the model can be concluded that, for the current MBL, the maximum draught for outbound vessels is 14.3m. The result is presented in Figure 4.14. Based on an interview with the Koole terminal ([Interviews Ship liner & Terminal, 2019-2020]) was concluded that the current market does not have a demand for this outbound vessel draught. Nevertheless, the model provides the insight that it is possible (for future market demands).



(a) Inbound vessel with a draught of 15m. Impact of suggested MBL's in terms of dredging volumes: dredge approx. 102.640m^3 more



(b) Outbound vessel with a draught of 12.7m. Impact of suggested MBL's in terms of dredging volumes: dredge approx. 11.534.532m^3 less

Figure 4.12: Results for *3e Petroleumhaven* trajectory

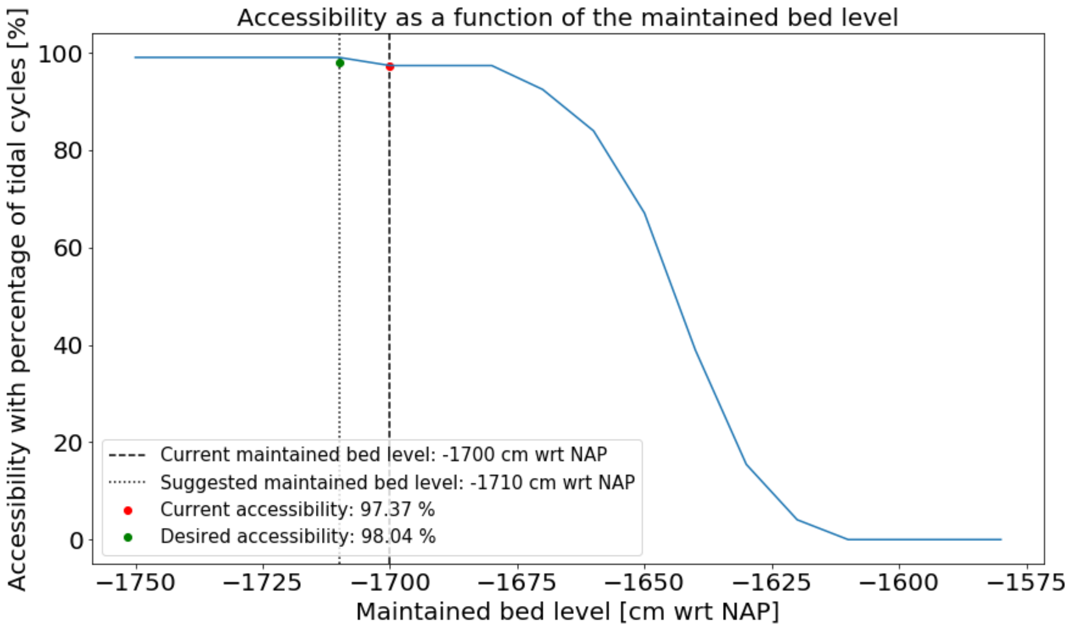


Figure 4.13: Detailed berth accessibility for a vessel with a draught of 15m (and 30 cm UKC)

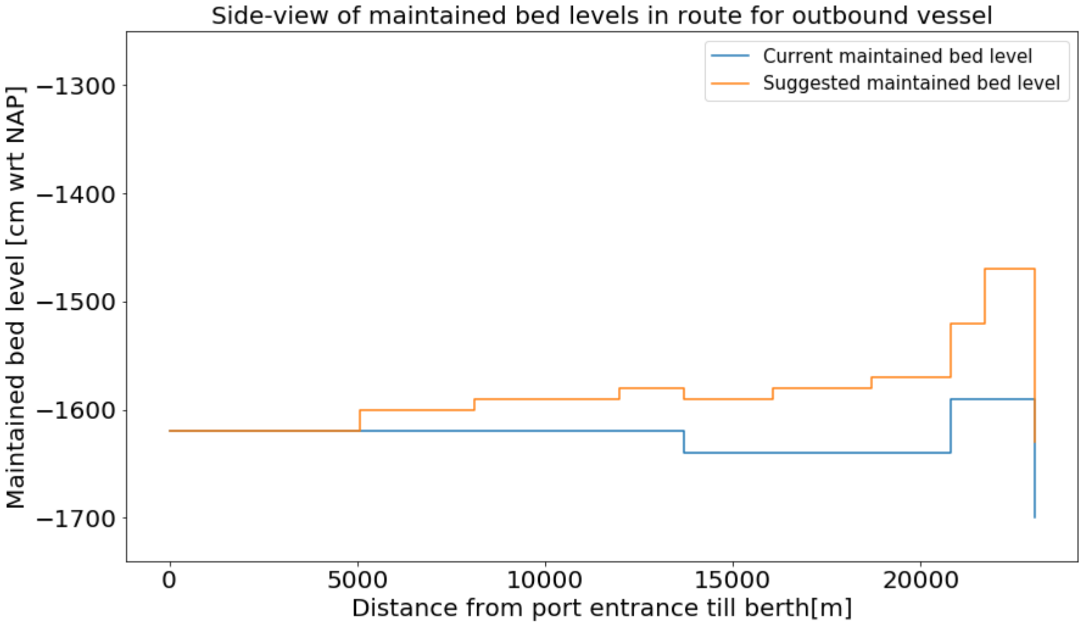


Figure 4.14: Result - outbound vessel *3e Petroleumhaven* trajectory with a draught of 14.3m. Impact of suggested MBL's in terms of dredging volumes: dredge approx. 1.896.702m^3 less

By dredging only 20cm extra between 0-5km, the entire route becomes accessible for outbound vessels with a draught of 14.5m.

Maeslantkering bottleneck analysis

A concept vertical design approach, by combining vessel-related factors into one factor, was presented in Figure 2.4. It became clear that bottom types also influence the UKC. The bottom type on the *Nieuwe Waterweg* can be considered as mud. However, at the *Maeslantkering* storm surge barrier, the foundation is concrete. If a vessel hits the concrete bed, the consequences will be larger compared to hitting a muddy bed. This should actually be included in the UKC policy, but is not. PIANC [2014] suggests adding 0.6m UKC for hard bottoms. The current UKC at the *Maeslantkering* is 10% of a vessel's draught. The largest-draughted vessels are 15m, so the UKC policy at this part of the route should be 2.1m (10% of 15m + 0.6m). Translated back to a percentage, this is about 14% of a vessel's local draught.

The *Maeslantkering* is located between km notation 5-10km. With the current and suggested MBL, the channel is accessible with 98.04% of the tidal cycles. An UKC of 10% of a vessel's local draught as imposed by the PoR was applied. When an UKC policy of 14% is inserted in the model, the channel is accessible with only 55.21% of the tidal cycles for the current MBL (-1640 cm wrt NAP). An MBL of -1680cm wrt NAP would be required to achieve the desired accessibility percentage again. The *Maeslantkering* would thus be a bottleneck in the route. This is a good example of why a port-network should be considered as a system.

4.5.2 'City' terminal

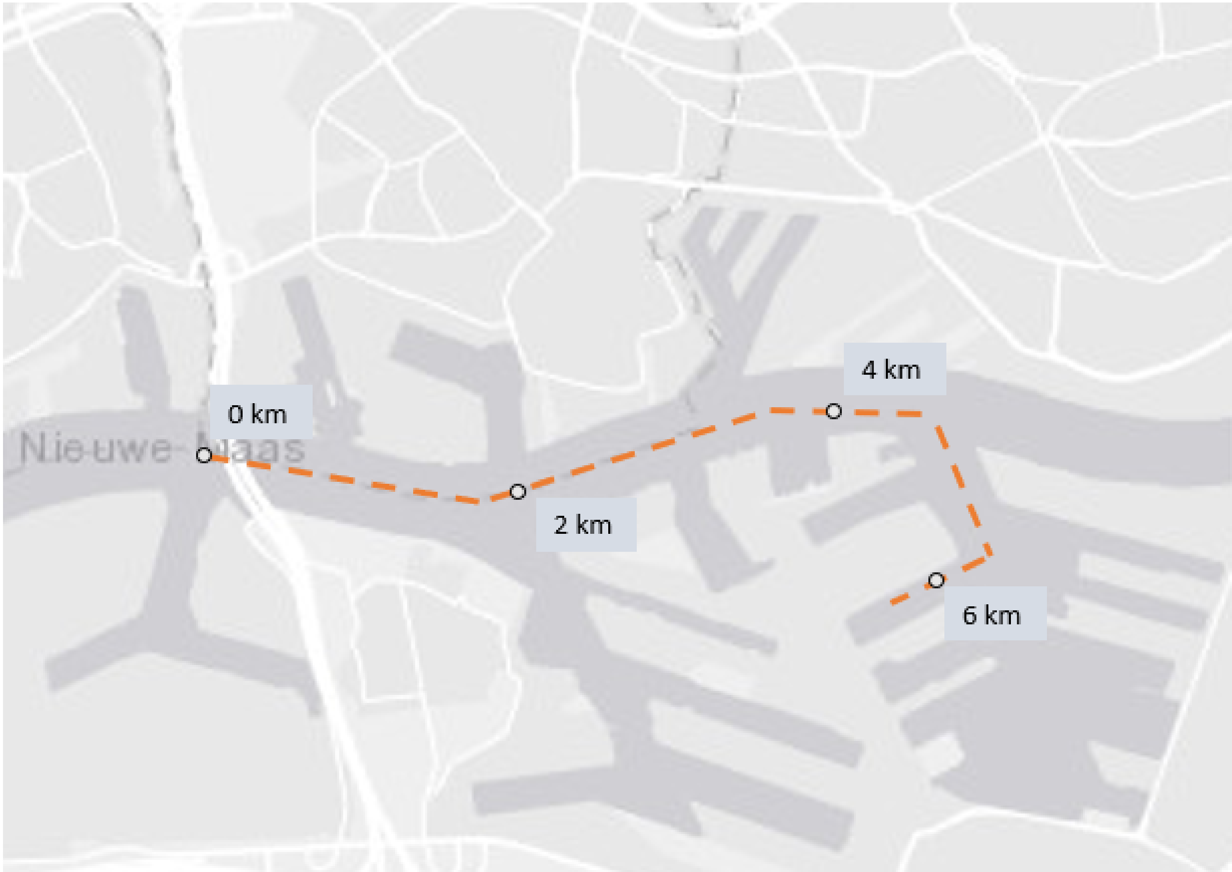


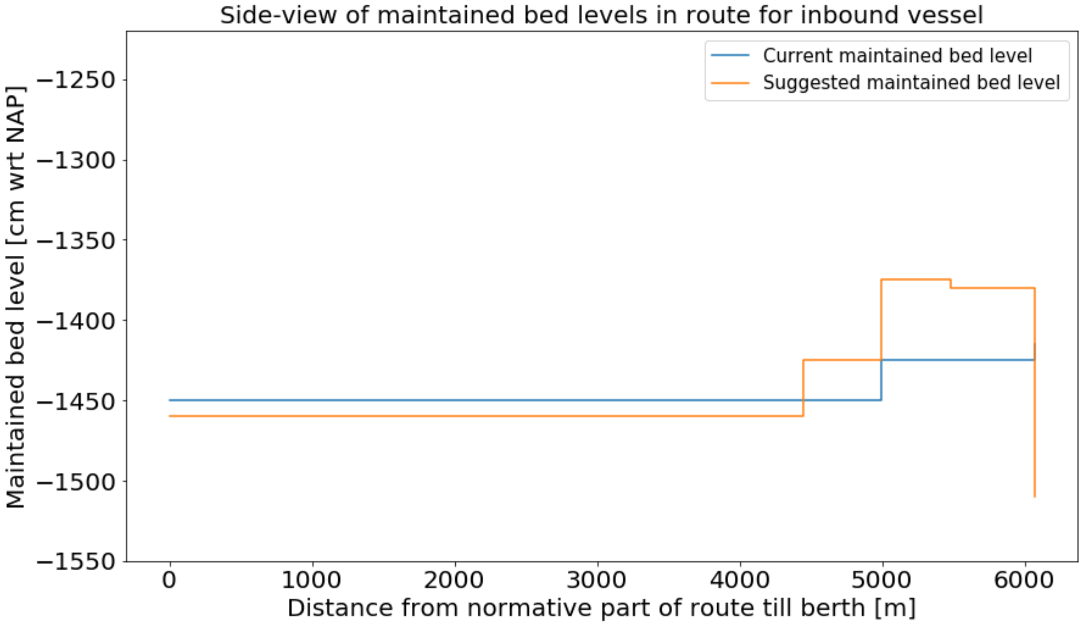
Figure 4.15: Spatial image with km notation for *Waalhaven* trajectory (from part with normative vessels on the channels till berth)

Output for current channel design

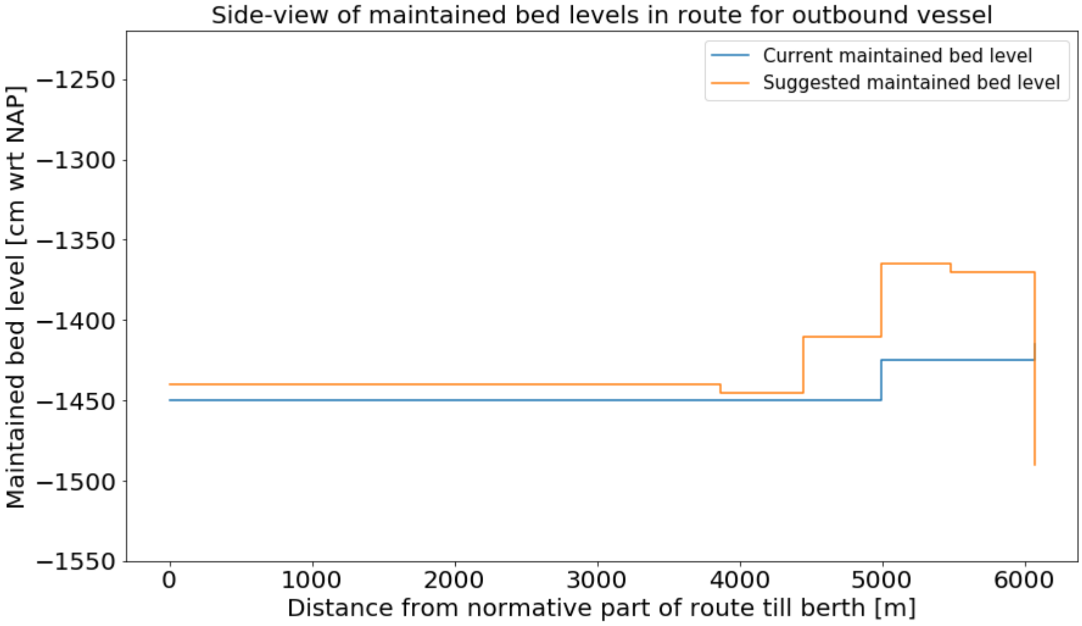
From Figure 4.16 it becomes clear that inbound vessels are critical for the vertical design of channels. However, the difference between the results of in- and outbound vessels are not that great. The difference in vessel draughts equals 20cm. The difference between the suggested MBL's is also approx. 20cm. This is because closer to the city, further from the sea, the tidal influences are less pronounced.

On the *Nieuwe Waterweg*, the model suggests only 10cm extra MBL. This is approx. between km notation 0-4km. The same result was found for the liquid bulk terminal case. The port basin manoeuvring area begins just after the 4km notation. The model suggests 25cm less MBL in this area. In the subsequent port basin, the model proposes 50cm less MBL. At berth, the model recommends 105cm more MBL. This is remarkable.

When studying the current design, the berth is less deep than the surrounding channels. This could only be explained if there are significant vessel motions (due to wave influences, for example) in channels, but this is not the case. It seems as if the MBL of the berth has already been adjusted to receive vessels with smaller draughts, because they have not visited the terminal for some time, as was concluded from the traffic data. The channels have not been adjusted accordingly. If these 13.5m vessels would visit this port basin again, there is sufficient water depth available in the fairway- and basin channels. This has also been confirmed by the pilot sailing this route (Interviews Port of Rotterdam [2019-2020]). With the current design and a recommended 30cm UKC at berth, this berth is not accessible. Figure 4.17 substantiates this with a detailed accessibility presentation of the berth. However, in practice, the accessibility could be increased by applying the ’always afloat’ principle (0m UKC at berth) and performing over-the-tide-operations (unloading before low tide). With 0m UKC at berth, the accessibility still only becomes 24.94% for a vessel with 13.5m draught.



(a) Inbound vessel with a draught of 13.5m. Impact of suggested MBL’s in terms of dredging volumes: dredge approx. 19.729m^3 less



(b) Outbound vessel with a draught of 13.3m. Impact of suggested MBL’s in terms of dredging volumes: dredge approx. 224.368m^3 less

Figure 4.16: Results for *Waalhaven* trajectory

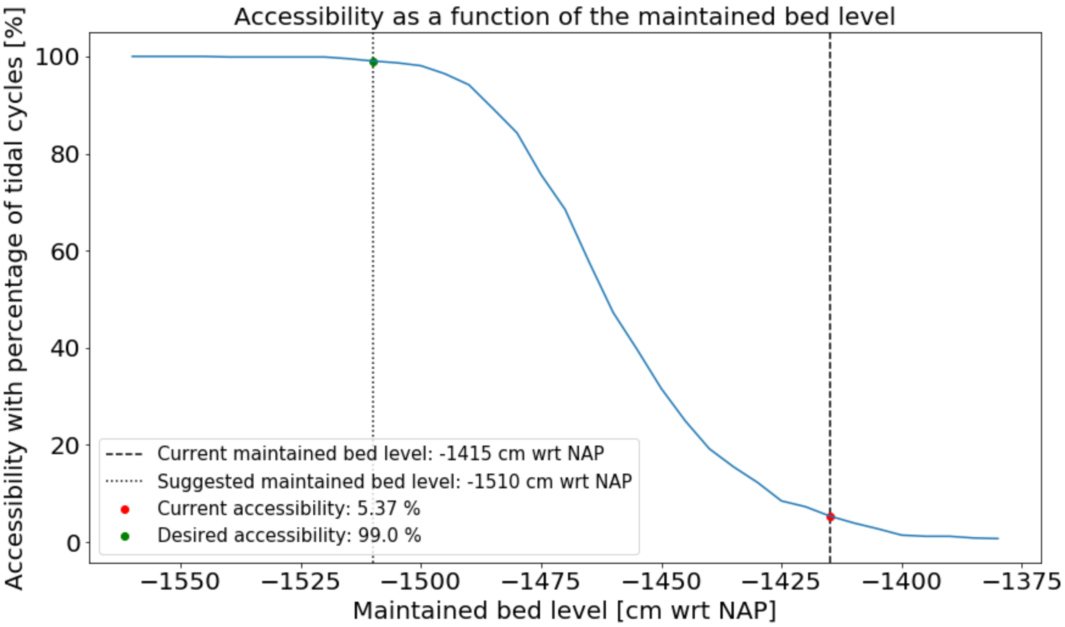


Figure 4.17: Detailed berth accessibility for a vessel with a draught of 13.5m (and 30cm UKC)

Alternative vessel draught scenario

The result of designing for a more actual draught of 13m is presented in Figure 4.18. Further reduction of the MBL's in the fairway- and basin channels is recommended. Moreover, a closer analysis on the berth is performed. A run is performed with 13m draught, and the 'always afloat' principle (0m UKC) is applied. This result is presented in Figure 4.19. The current accessibility becomes 97.26% for the largest-draughted vessels visiting this basin at the moment. HCC must analyse local water levels critically. If an UKC of 30cm is applied at berth, the current accessibility becomes only 61.6%. However, these percentage could be increased in practice with over-the-tide-operations (unloading before low tide).

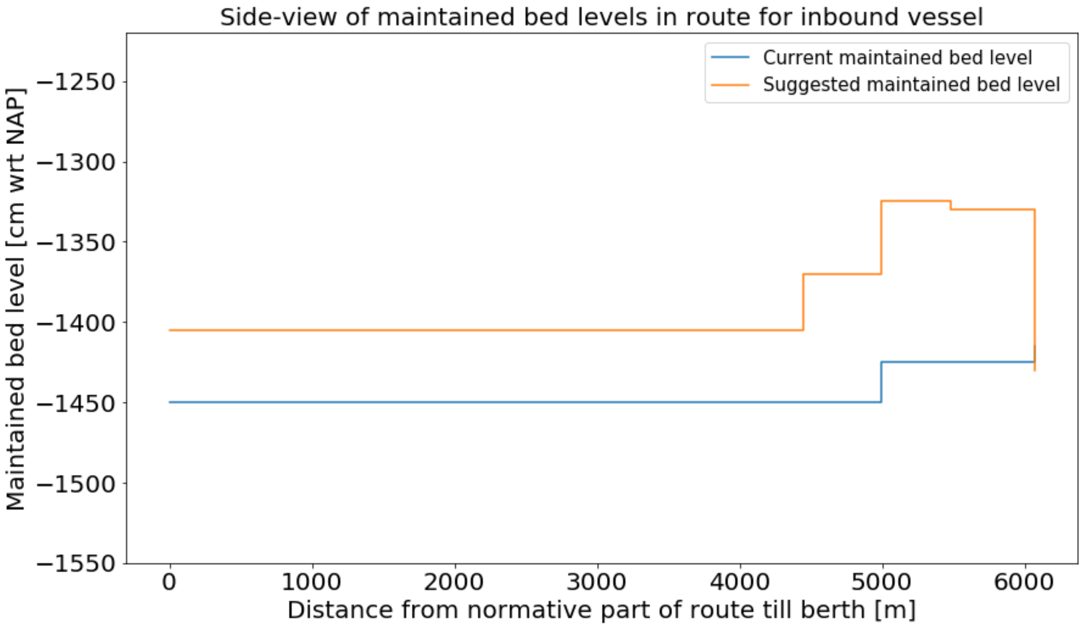


Figure 4.18: Result for inbound vessel *Waalhaven* trajectory with a draught of 13m. Impact of suggested MBL's in terms of dredging volumes: dredge approx. $681.517m^3$ less

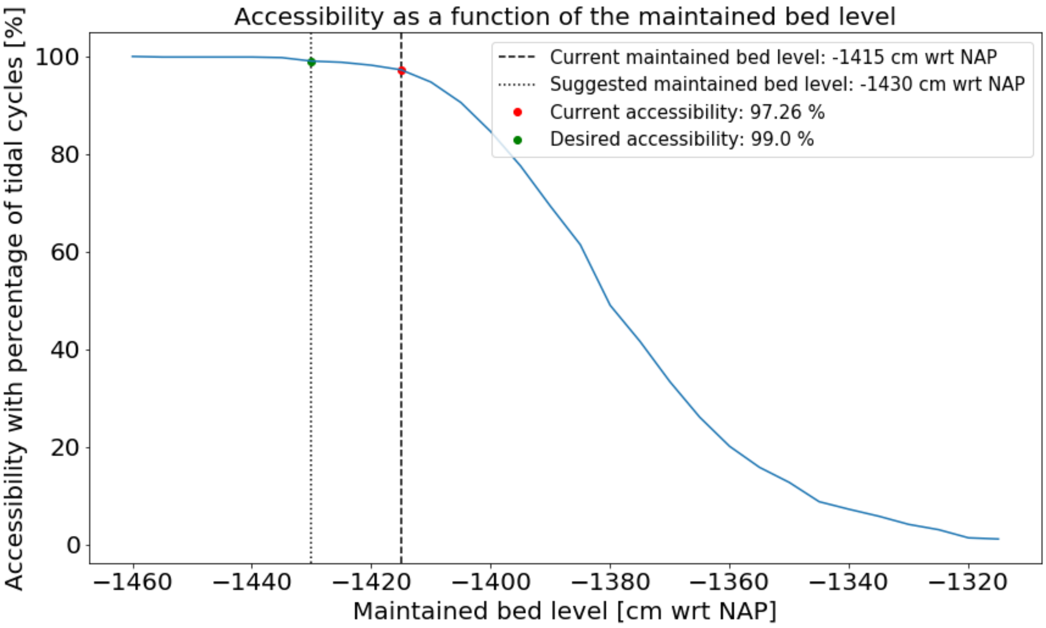


Figure 4.19: Detailed berth accessibility for a vessel with a draught of 13m (and 0m UKC)

4.5.3 Dry bulk terminal

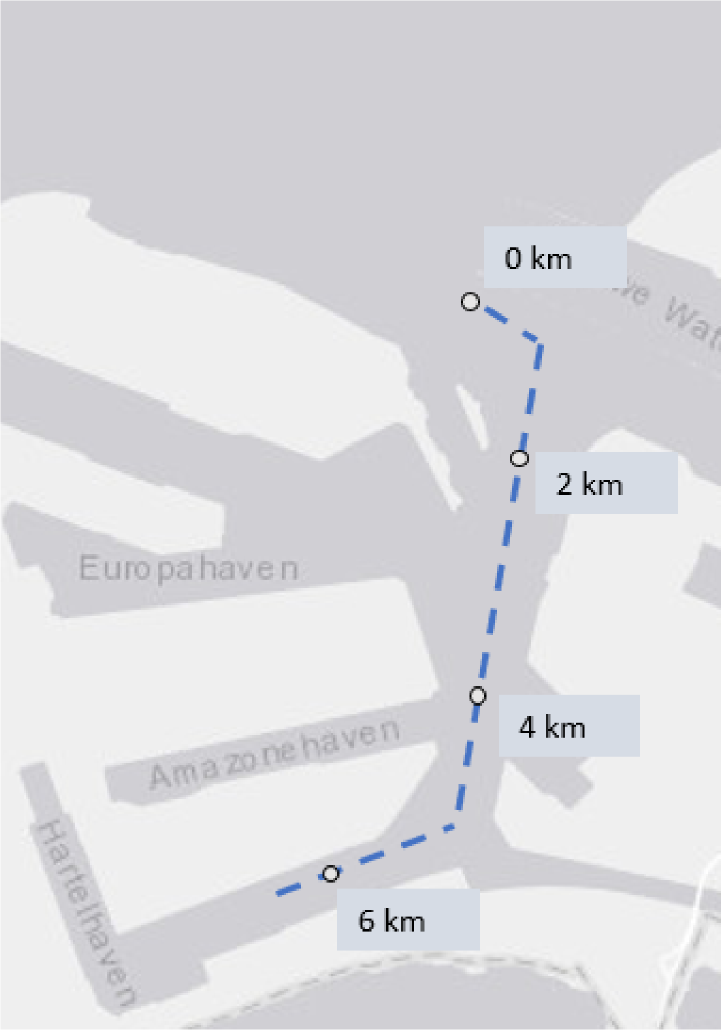


Figure 4.20: Spatial image with km notation for *Mississippihaven* trajectory (from port entrance till berth)

Output for current channel design

As stated in Table 4.1, the draught for which channels on the *Mississippihaven* trajectory have been designed equals 22.6m. The largest observed outbound actual vessel draught was 18.6m. So for the vertical design, only inbound vessels have to be studied. The result is presented in Figure 4.21.

The recommendations are small on this route, order size 5-20cm. In the current design, the MBL is increased between km notation 5-6km. This is in the port basin. It seems as if a different UKC policy is applied here for the design. Other factors definitely do not change. However, this is not in accordance with the current UKC policy (Appendix B.4). For the largest-draughted vessels (>17.4m), the UKC policy does not change in the port basin. Hence, it is unclear why the current MBL increases in the port basin.

At the berth, there is a recommendation to increase the MBL with 190cm. Apparently, the berth is currently not available for vessels with a draught of 22.6m. The berth accessibility is presented in Figure 4.22. This is also consistent with the observation from Section 4.3.3; the draught for which channels were designed (22.6m) was last (almost) reached in January 2016. Since May 2016, the largest actual vessel draught has been 18.6m. The berth seems to be maintained for a different vessel draught, but the channels not. They are still maintained to facilitate 22.6m vessels.

From an interview with the business manager of this terminal (Interviews Port of Rotterdam [2019-2020]) was concluded that considerable dredging costs could be saved by maintaining channels for a more recent actual vessel draught.

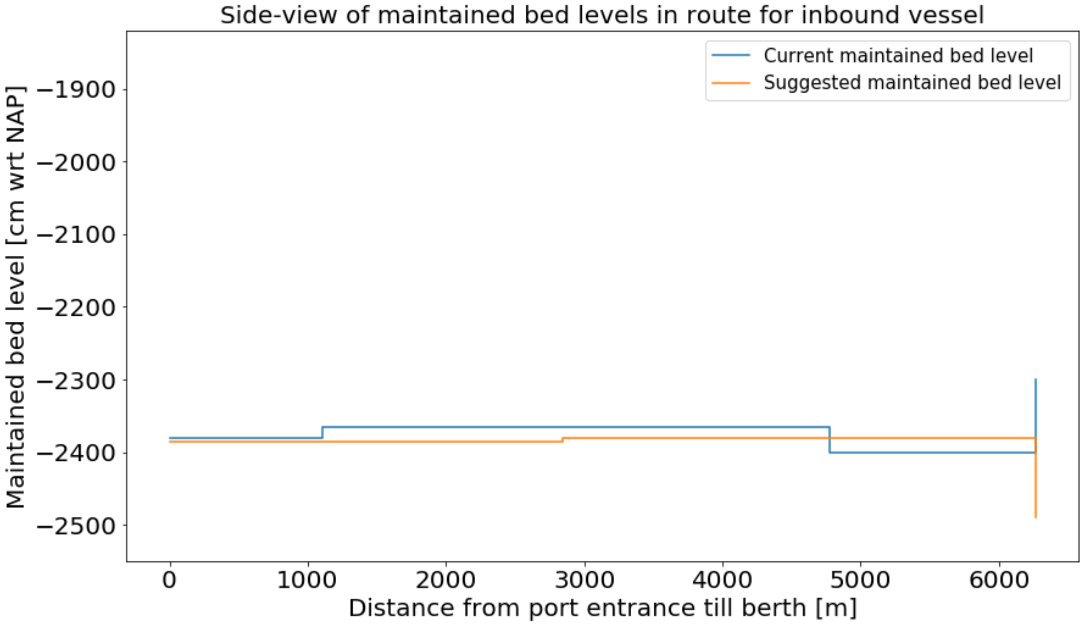


Figure 4.21: Result for inbound vessel *Mississippihaven* with a draught of 22.6m. Impact of suggested MBL's in terms of dredging volumes: dredge approx. 176.949m^3 more

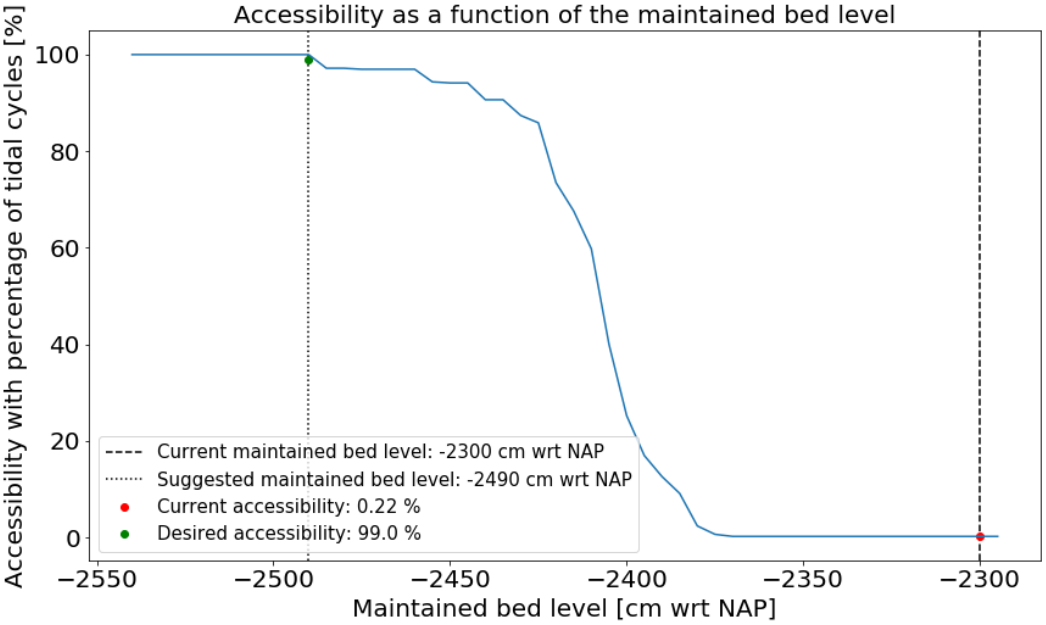


Figure 4.22: Detailed berth accessibility for a vessel with a draught of 22.6m (and 30cm UKC)

Alternative vessel draught scenario

The model result with a more actual vessel draught is presented in Figure 4.23. The result is significant. approx. 7.013.037m^3 less material has to be dredged when designing for the largest draught that has been achieved since May 2016. In addition, an analysis was carried out to determine for which vessel draught the berth is currently maintained. The answer is approx. 20.8m.

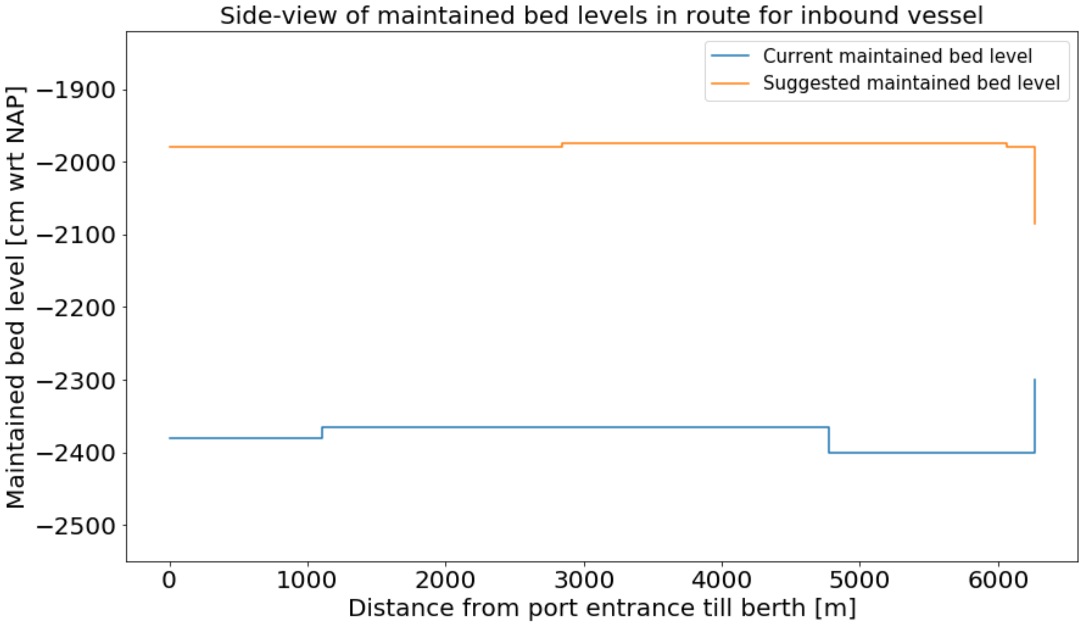


Figure 4.23: Result for inbound vessel *Mississippihaven* with a draught of 18.6m. Impact of suggested MBL's in terms of dredging volumes: dredge approx. 7.013.037m^3 less

4.5.4 Container terminal

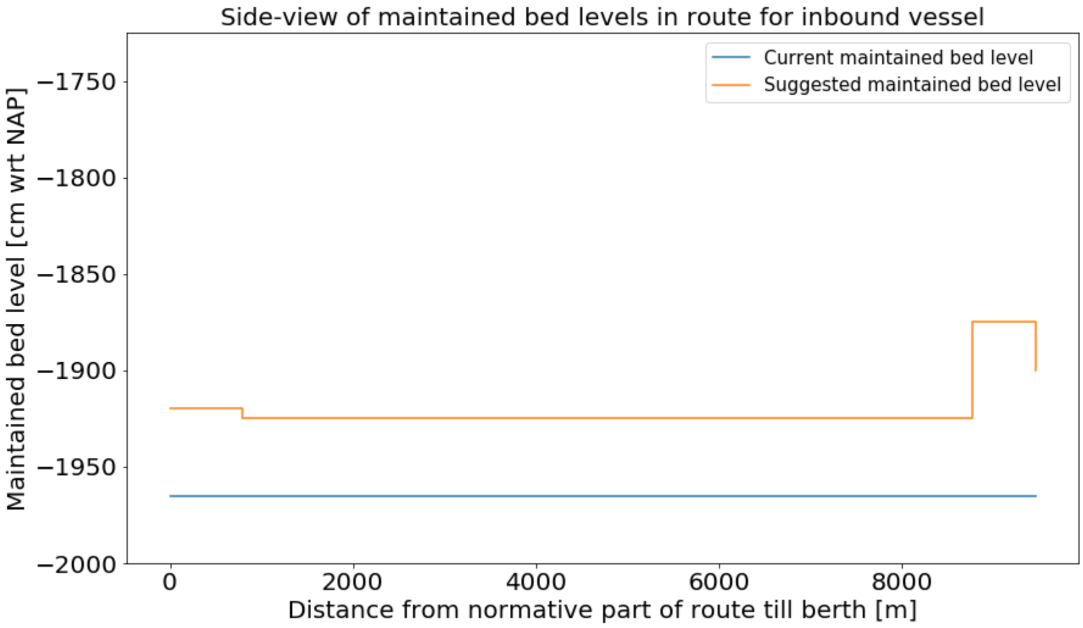
Figure 4.24: Spatial image with km notation for *Prinses Amaliahaven* trajectory (from part with normative vessels on the channels till berth)

Output for current channel design

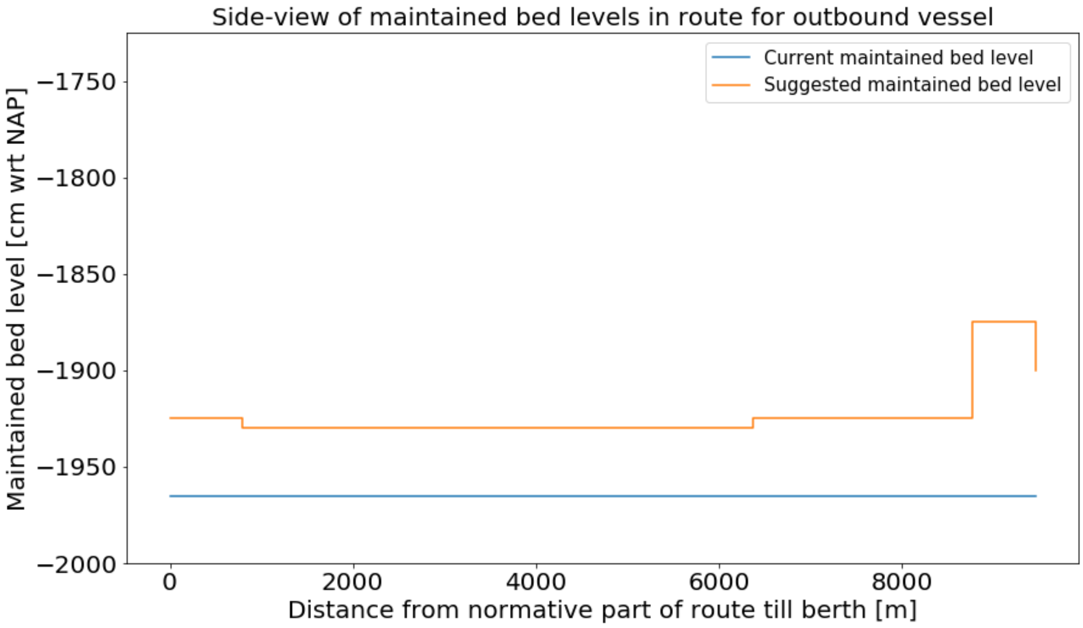
Most important for this case was to remember that it is the only one without a tidal window and that it is built to handle larger vessel sizes in the future. The results of the model for vessels with a draught of 17m are presented in Figure 4.25.

Currently, the entire route has got the same MBL (-1965cm wrt NAP). This does not make sense and is inconsistent with the PoR's design approach, because the UKC policy changes throughout the route. UKC policy influences the required MBL. In Appendix F an example calculation is made by simply using PoR's own design approach. The recommendations are in the order of 10-80cm less MBL. The model's recommendations are between 45-90cm less MBL. From this observation can be concluded that the PoR's design approach is slightly more conservative than the model. This is understandable since the model includes local conditions of 429 days and the PoR uses a safe extreme low water level (based on ALAT and HME).

The only difference between in- and outbound vessels, in this case, are the vessel speeds. Between approx. km notation 0-6km, 5cm more MBL is recommended for outbound vessels. This is because they sail more slowly at this part of the route compared to inbound vessels (Table 4.2). The chance of encountering a low water level therefore increases. However, the difference of 5cm MBL is almost negligible. Nevertheless, outbound vessels are apparently normative for the vertical design of channels in this case.



(a) Inbound vessel with a draught of 17m. Impact of suggested MBL's in terms of dredging volumes: dredge approx. 1.730.880m^3 less



(b) Outbound vessel with a draught of 17m. Impact of suggested MBL's in terms of dredging volumes: dredge approx. 1.605.290m^3 less

Figure 4.25: Results for *Prinses Amaliahaven* trajectory

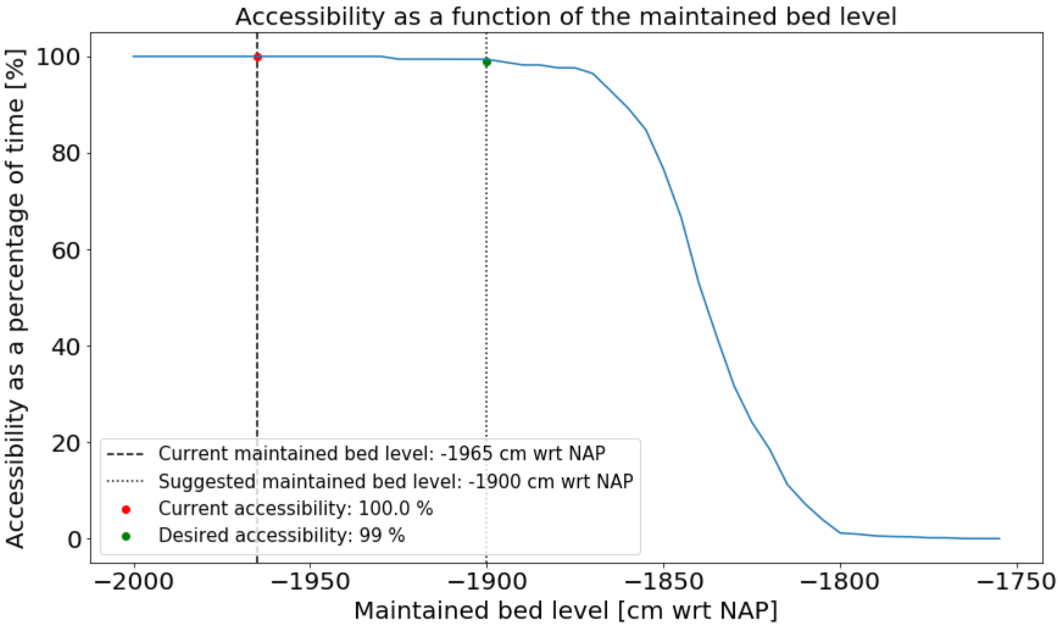


Figure 4.26: Detailed berth accessibility for a vessel with a draught of 17m (and 30cm UKC)

Alternative vessel draught scenario

The result when designing for 16.5m, as described in Section 4.3.4, is presented in Figure 4.27. The benefits in terms of dredging volumes are significant. For outbound vessels with a draught of 17m, it was 1.605.290m^3. For 16.5m, it has become 3.534.840m^3. Hence, the benefit when designing for this draught equals approx. 1.929.550m^3 (3.534.840 - 1.605.290).

Between approx. km notation 2-6km, the model recommends 35cm extra MBL. This is where the bottleneck arises for larger-draughted vessels. When performing an analysis with the model, it turns out the *Prinses Amaliahaven* is currently designed to handle vessels with a draught of 17.35m (for 99% of the time). The result is presented in Figure 4.28.

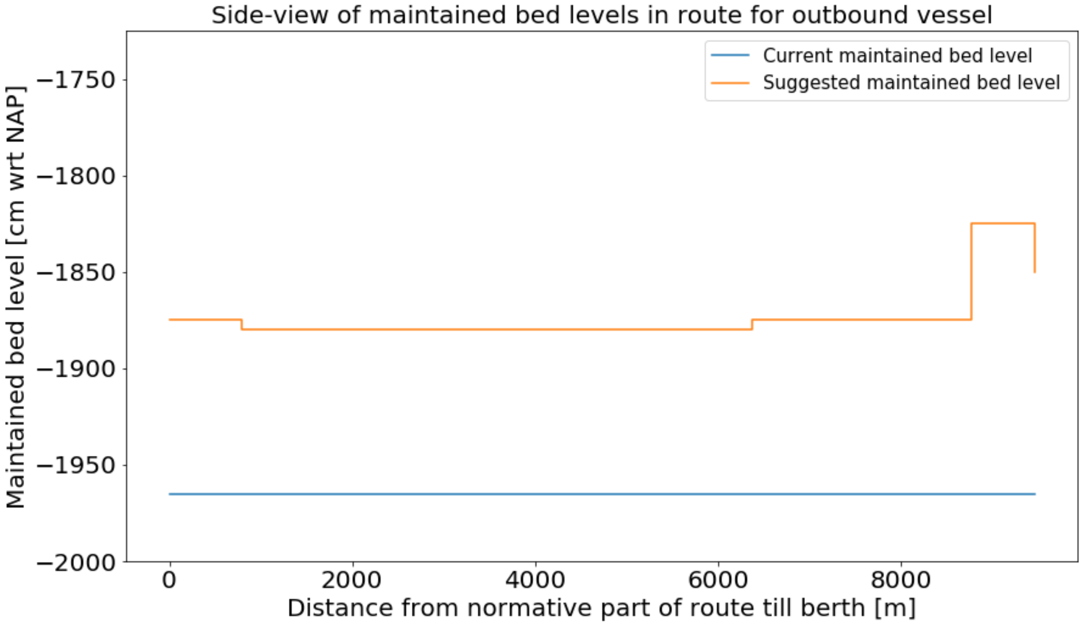


Figure 4.27: Result for outbound vessel *Prinses Amaliahaven* with a draught of 16.5m. Impact of suggested MBL's in terms of dredging volumes: dredge approx. 3.534.840m^3 less

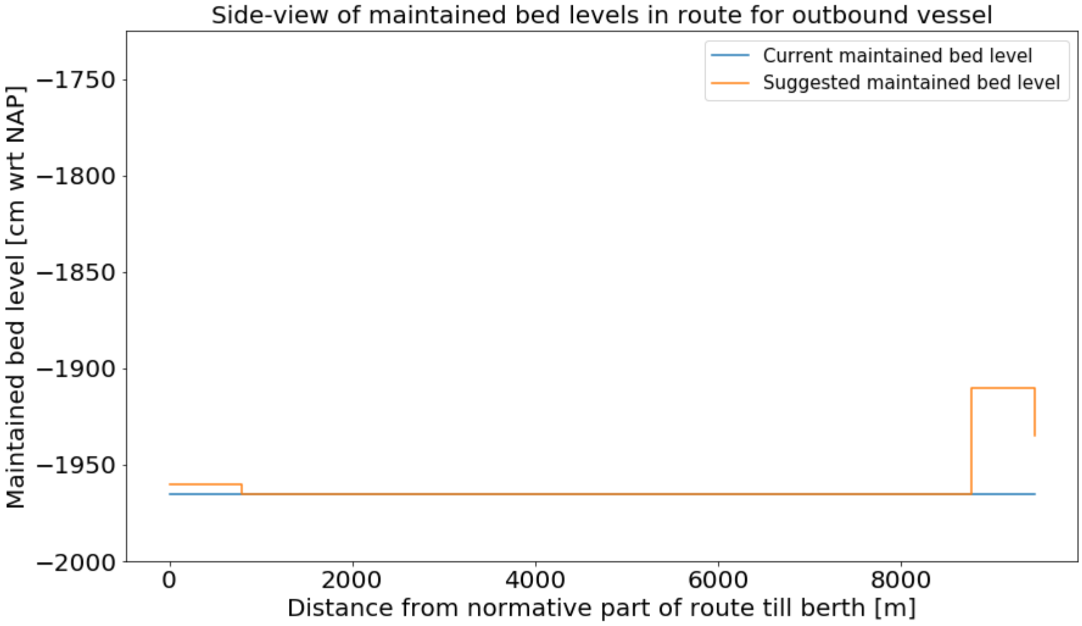


Figure 4.28: Result for outbound vessel *Prinses Amaliahaven* with a draught of 17.35m. Impact of suggested MBL's in terms of dredging volumes: dredge approx. 206.585 m^3 less

4.5.5 Overview of accessibility percentages cases

Accessibility percentages can vary over a route. Hence, there are bottlenecks. An overview of current accessibility percentages in the port-network is presented in Appendix G.

4.6 Parameter sensitivity analysis

The influences of parameters on the channels of the *3e Petroleumhaven* trajectory will be analysed. As mentioned in Section 4.4.4, the *3e Petroleumhaven* is the only case with a point-based tidal window. In practice (assessed by HCC), there is a window around this access moment, which is approx. ± 30%. The influence of this parameter on the accessibility will be assessed in this section. In addition, vessel speeds determine which water levels a vessel encounters on a route (in relation to a tidal window). The influence of vessel speeds on the MBL's of the *3e Petroleumhaven* trajectory will also be researched. Finally, the influence of vessels' duration at berth will be analysed.

For the presented results, the inbound vessel draught of 15m (for which channels are designed) is still applied. In addition, the UKC policy as imposed by the PoR is applied. Likewise, the same fresh water allowance is used.

4.6.1 Window around point-based tidal window

The point-based tidal window for in- and outbound vessels at the *3e Petroleumhaven* is 0.5kn while flood-currents are decreasing. The results for varying windows around this specific accessibility moment are presented in Table 4.4. The smaller this window becomes, the smaller the number of potential accessibility moments. This is not a surprise. However, the effect on the MBL's is quite significant. The larger the window, the more accessibility moments and the greater the chance of encountering low water levels. As a result, the MBL's (and thus dredging volumes) increase as the window becomes larger.

	Window around point-based tidal window					
	0	±10%	±20%	±30%	±40%	±50%
Highest potential accessibility	0	68.14%	98.08%	99.04%	99.64%	99.64%
Impact in terms of dredging volumes [m^3] (negative value = dredge less)	n/a	-1.710.094	-223.352	102.640	659.448	659.448
Impact on dredging volumes compared to applied ±30%	n/a	-1887%	-333 %	0	589%	589%

Table 4.4: Influence of varying windows around point-based tidal window

4.6.2 Vessel speeds

Vessel speeds were presented in Table 4.2. For this sensitivity analysis, the average vessel speeds on the *3e Petroleumhaven* trajectory are adjusted in the range of ±10-30%. This is also approximately the range with which the minimum and maximum speeds are reached. The result is presented in Table 4.5. By slowing down, more MBL is needed. This can be explained, because the tidal window is 0.5kn while flood-currents are decreasing. If a vessel reduces speed on the route, it has to start sailing earlier to arrive at the tidal window in time. Sailing earlier means, for this tidal window, with a lower tide and hence lower water levels. It is understandable that more MBL is needed when slowing down on the trajectory. However, the influence appears to be strong; dredging volumes are increasing rapidly with slower speeds. There are no benefits to sailing faster than the average speeds.

	Deviation from average vessel speeds						
	-30%	-20%	-10%	0	+10%	+20%	+30%
Impact in terms of dredging volumes [m^3] (negative value = dredge less)	379.873	193.624	97.885	102.640	102.640	102.640	102.640
Impact on dredging volumes compared to average speeds	296.9%	102.3%	2.3%	0	0	0	0

Table 4.5: Influence of varying vessel speeds on *3e Petroleumhaven* trajectory

4.6.3 Duration at berth

If vessels are moored for a longer period of time, the chance of encountering a low water level increases. This is reflected in the result of Table 4.6. The longer a vessel remains at berth, the more MBL is required. This is up to a certain limit, when the lowest water level will most likely be reached (5.8 days in this case). In the analyses of the model, no relationship was found between the MBL of the fairway- and/or basin channels and the duration at berth.

	Duration at berth [days]				
	0.1	3.0 (minimum)	5.8 (average)	7.2 (maximum)	10
Berth MBL *3e Petroleumhaven* [cm wrt NAP]	-1640	-1680	-1710	-1710	-1710

Table 4.6: Influence on the MBL of the berth for varying durations at berth

This is a statistical approach. For design purposes, the maximum duration at berth should be applied. However, if vessels are moored for a relatively short duration in the future (due to operational developments), the tidal window may influence the encountered low water level at berth.

4.7 Conclusion

The MBL model has been applied to four cases in this chapter. Based on the performed analyses, the sub-research question below can be answered.

To what extent can a statement be made, based on traffic data, on how often the available water depth is used?

From the traffic study, it was concluded that there can be a significant discrepancy between actual and design vessel draughts. For example, only <0.1% of the largest container vessels (16-17m vessel design draught) handled in the *Prinses Amaliahaven* (almost) reach the draught for which channels has been designed (17m). In addition, less than 20% of these container vessels achieve an actual draught of 15m. Also, the draught for which channels have been designed in the *Mississippihaven* (22.6m), was last (almost) reached in January 2016. The largest draught that has been reached since May 2016 is 4m below the design draught (18.6m). Based on interviews (A.3), the following could be concluded: if shipping lines would better coordinate their expected actual draughts with a terminal for a certain period, a win-win opportunity arises for port authority, terminal and shipping company because dredging costs can be saved.
Moreover, the liquid bulk terminal case (*3e Petroleumhaven*) provided the insight that other factors may also play a role as to why not all depth is used. Vessels on the *Nieuwe Waterweg* are allowed to sail with a maximum draught of 15m, while the vessel's design draught equals 17m. This is because the *Nieuwe Waterweg* cannot be deepened further due to the national interest in limiting salt intrusion [Interviews Port of Rotterdam, 2019-2020]. In addition, further deepening is limited by the concrete foundation of the *Maeslantkering* (storm surge barrier). A *Maeslantkering* bottleneck analysis was performed in Section 4.5.1.

What observations can be made for the Port of Rotterdam (case study)?

Specific recommendations can be made for each case. These are also described in detail in Section 4.5. It can be concluded that by designing with the model, interesting insights emerge. The model has shown that for the current MBL's, accessibility percentages can differ over a trajectory. Hence, there are bottlenecks in routes. For example; by dredging only 10cm extra between km notation 14-21km, the accessibility of the entire *3e Petroleumhaven* trajectory increases from 94% to 98%. With the recommendations of the model, the accessibility percentages over a trajectory can be aligned. This does not even necessarily mean that more dredging is required. In fact, by revising the MBL's for the 'city' and 'container' case, less net dredging is required and the accessibility can be increased.

Moreover, some current MBL's are not logical at all. On the same route, it sometimes seems as if fairway- and basin channels are designed for a different draught than the berth (dry bulk and city case). Channels are no longer used for the draughts they have once been designed for. By maintaining channels for more actual vessel draughts, significant dredging activities (and hence costs) can be saved. For the 'dry bulk' case, this amounts to even more than 7 million m^3 of dredging volume. Also, the vertical design of the *2e Maasvlakte* is not consistent with PoR's design approach. Changes in the UKC policy are not reflected in the vertical design. In addition, the *Rottepeil* (-0.65m NAP) in the city centre of Rotterdam was used as the reference level. The *2e Maasvlakte* is approximately 40km located from the city centre. A normative low water level of -1.10m NAP should have been applied. So even by using PoR's own design standards, instead of the model, suggestions for improvement can be made. Overall, it can be concluded that the accessibility and use of existing channels should be reviewed once in a while.

A final recommendation would be to specify an outbound vessel draught for which channels are designed. Ports tend to pay more attention to inbound vessels and less to outbound vessels when designing channels. This is because inbound vessels are often normative for the vertical design. However, this is not always the case. Also, this difference may be due to the more complex nature of outbound vessels. Figure 2.2 also showed that in- and outbound vessels can encounter different water levels. The model can provide support to specify outbound vessel draughts and has also demonstrated this.

5 Discussion

This chapter discusses the interpretation of the results, as found in Chapter 4. Some limitations of the study will be acknowledged. In addition, other practical applications of the model are presented.

5.1 Dredging activity (*Mississippihaven*)

The 'dry bulk' case revealed that by designing with actual vessel draughts, more than 7 million m^3 of dredging volume could be saved. This is immense. A Reason to nuance this conclusion emerged from interviews with the dredgers. The EMO terminal is still paying for MBL's to handle vessels with a draught of 22.6m. So the PoR is still contractually bound to facilitate these MBL's. However, because they know that little or no use is made of these MBL's, the priority of maintaining these channels has been reduced in consultation with HCC. However, if a vessel announces itself with a draught of 22.6m (which is at least 24 hours in advance), sufficient water depth has to be available to comply with the contractual obligations. It is not possible to dredge the entire port basin in 24 hours. Therefore, the smaller prioritisation is limited to just urgent spots removal on the channels and at the berth. The berth must obviously be available in order to do so. Urgent dredging is more costly than normal maintenance dredging.

In 2021, a new terminal, the Hartel terminal, will become operational in the *Mississippihaven.* It is designed for vessels with a draught of 21.0m. Hence, the channels will become better utilised in the near future. However, this does not alter the fact that savings could have been made in recent years (dredging maintenance works for the PoR and the related costs passed on in the contract with the terminal) by considering actual vessel draughts.

5.2 Adjusting accessibility percentages

Reducing accessibility percentages and the related maintenance costs could be passed on in the contract with terminals. Whether this could be a new addition to their business case was asked during an interview with the Koole terminal ([Interviews Ship liner & Terminal, 2019-2020]). From this interview was concluded that they would most likely not opt for a lower accessibility percentage, even if this saves lease fees (due to dredging savings from the port authority). A vessel cannot be planned on a specific date. If a vessel arrives at the port and cannot enter, it will cost the charterer about €35.000,- per day (for a 15m draught vessel class). This causes too much damage to a customer's business case. On the terminal side, there is also well in advance ensured that everything is ready to handle the vessel. Surprises regarding accessibility would also mess up the operational planning and incur more costs than benefits.

5.3 Model application limitations

Multiple tidal windows & air-draught

The MBL assessment model is not set up to consider multiple access restrictions on a route. So it cannot be applied to a route with multiple tidal windows. Also, in the PoR, the model cannot be applied to a route to *Dordrecht* for example; there is an additional water level restriction at the *Botlekbrug* (bridge) due to air-draught.

Over-the-tide operations

Accessibility percentages at the berth can be increased with over-the-tide operations; unloading a vessel while the water level is decreasing. The model does not consider the fact that a vessel's draught can decrease overtime at the berth. Over-the-tide operations are only sometimes applied at container-terminals in the PoR.

Baltic Sea Region

The MBL model is less interesting for ports in the Baltic Sea Region. In this region, tidal influences are only a few centimetres (negligible). The Baltic Sea is too small to generate its own significant tidal variations, and the connection to the North Sea is too narrow to be influenced by the North Atlantic tides. So water levels do not vary too much, and there are no tidal window related challenges. By measuring the available water depth and calculating the required water depth, it is relatively easy to select a sufficient MBL.

Data availability
The PoR is one of the smartest ports in the world. They collect a lot of data. To run the MBL model at other ports, local conditions data must also be available there. Water levels have to be measured throughout the port, and currents have to be measured at locations where tidal windows are in effect.

5.4 Simplifications and uncertainties

Dimensions of channels
The dimensions of channels (Appendix E.3) were determined to express the impact of adjusting the MBL's in terms of dredging volumes. The length of the edges was obtained from the network. The width was subsequently based on the surface area of the maintenance area. The result was manually measured in port maps as a check. However, edges and maintenance areas do not fully overlay. The resulting dredge volumes have to be interpreted as an approximation. Also, the fact that the length of a vessel's route can be slightly different in practice compared to the route in the network does not matter much. With AIS data, the duration in channels has been determined and has been converted to vessel speeds (Appendix E.2.2). So if a route is longer in practice, it will have resulted in a slightly higher vessel speed than the actual speed. This does not matter for the calculations as it revolves around the duration in a channel (edge) and encountered water levels. Moreover, the AIS tracks of four in- and outbound vessels were analysed for most cases. This is relatively little. Often there was not more data available, because these largest vessels for which has been designed have not visited the terminals more often. The same holds for the duration at berth analyses, which was based on five vessels per case.

Local conditions data
The local conditions data consists of 429 days. Since there are trends of longer periods in astronomical tides, it must be kept in mind that conditions may be different in the future. Moreover, historical predicted water levels (by the PoR) were used. This is based on measured water levels and astronomical predictions. The difference between predicted and measured water levels is small, maximum a few cms. Predicted water levels were used because pieces of data were regularly missing in the measured water levels data-set. In addition, the water level data-sets goes in step sizes of 10 minutes. If a vessel is somewhere at a certain time and it has to be linked to a water level, the time step is rounded off in 10's of minutes. The maximum deviation between actual and rounded time is therefore five minutes. The margin of error in the selected water level is negligible. Furthermore, water levels are not measured at the exact location of a vertex. Each vertex is linked to the nearest water level measurement point. In practice, HCC at the PoR asses locations in the port the same way [Interviews Port of Rotterdam, 2019-2020]. The closest water level measurement, in terms of distance and time, is used.
A choice could have been made to extrapolate between measurement water level points. This has not been done because the tidal offset (water level drop) over an entire route is not that large. For the considered cases, the tidal offset for inbound vessels is in the order of magnitude 10-30cm and for outbound vessels 30-60cm (Appendix B.3). Since there are several measurement points along a route (Figure 4.6), and there is also a margin of error in the extrapolation, this was not done. Measuring water levels at more places in the port would still be a recommendation. The vertices could, for example, be placed on every km of the navigation channel.

Actual vessel draughts
There is a margin of uncertainty in the actual vessel draughts as presented in Section 4.3. To begin with, the actual draughts are communicated verbally or in writing by captains and agents. Human errors are sometimes made in this communication (and noting down) of the actual draughts. This was noticeable because some actual draughts in the data were ten times too large due to a comma error. Moreover, actual vessel draughts are determined by a computer in the vessel. Just before a vessel is about to depart, so when it is fully loaded, the actual draught is calculated. This is the statical draught measured at berth. This is also converted to the statical draught in saltwater. Local water density is required input. The local water density can be measured, but sometimes just an assumption is made. The calculated draught is compared to the Plimsoll mark for checking. Subsequently, the computer can calculate and predict, based on expected fuel and freshwater (by crew) consumption, what actual draughts will be. When calling at a port, the most recent actual draught is communicated (converted to saltwater and statical). So there is a certain inaccuracy in the actual draught because it is calculated by a model, water densities are not always measured, and human errors can be made while communicating the actual draught.
According to Savenije [1995], the difference between the announced draught and the actual draught in the Port of Rotterdam is about +7cm, with a variance of 15cm.

5.5 Other model applications

Relate UKC to vessel speeds
Different UKC policies are applied at fairways, basins and berths. An important reason for this is because vessel speeds differ for these port sections. The faster a vessel sails, the more squat occurs, the more UKC is required. So there is a relation between UKC and vessel speed. In the model, it is possible to apply smaller UKC's for slower vessel speeds on trajectories. So it could be possible to relate vessel speeds to UKC policies. Subsequently, the impact on required MBL's (and dredging works) can be quantified.

Variation of vessel speeds
Moreover, this research has shown that vessel speeds have a strong influence on the required MBL. Average, minimum or maximum vessel speeds have been used for analyses on trajectories. So an extreme or average has always been chosen for the entire trajectory. A combination or variation has not been applied. This could be performed.

6 Conclusions and recommendations

The objective of this research is to identify opportunities to make more efficient usage of the available water depths in ports. To reach this objective, one main question and several sub-research questions were defined. These questions contribute to concluding on the research objective. In this chapter, answers to those questions are provided. The sub-research questions are addressed in sequential order in Section 6.1, concluded with the main question. Subsequently, recommendations for further research are made in Section 6.2.

6.1 Conclusion

Firstly, the sub-research question below was addressed:

How are maintained bed levels determined, and what are the opportunities for improvement?

PIANC guidelines have broad international support and can be considered as a generally accepted approach. These guidelines provide the most concise build-up of factors to consider when determining a MBL. The guidelines are designed to facilitate safe navigation and can be used anywhere. Because they are so general, the results are often conservative and can vary widely. The two most influential factors for MBL calculations are the draught for which a channel has been designed and the UKC.

As for UKC, there is no international agreement on the UKC build-up and related factors. The required UKC is highly dependent on a location and situation. Determining an appropriate UKC based on theory is therefore difficult. Based on the previously mentioned and interviews with experts, it is concluded that UKC policies are understandably often based on experience and iteration [Interviews Royal HaskoningDHV, 2019-2020]. Moreover, shipping lines and port authorities can have a different perspective on UKC factors to consider and hence policy. Shipping lines sometimes sail with a safer margin than a port imposes on them because they prefer their own for safe navigation. This is achieved at the expense of cargo. This could be overcome if a port would have an IMO-certificate for standardised best industry practices (for designing channels, acquiring local data and making forecasts), which doesn't exist yet.

Furthermore, actual vessel draughts are currently not considered in the vertical design of channels. There can be a discrepancy between actual vessel draughts and the draught for which a channel has been designed.

For a location, how is accessibility determined?

With regard to the vertical design of a channel, the accessibility depends on the available and required water depth. The available water depth is related to the MBL and water levels (tides). The required water depth is related to vessel characteristics and local policies for safe navigation. Moreover, for accessibility, a distinction between trajectories with tide-bound and non-tide-bound vessels has to be made.

Trajectories with non-tide-bound are designed to allow accessibility at all time (excluding extreme conditions). For tide-bound vessels, a vertical and/or horizontal tidal window may apply. With a vertical tidal window, a vessel has to wait for high(er) water levels. In addition, if currents are too strong for a vessel to navigate or manoeuvre safely during a period in the tidal cycle, a horizontal tidal window can be applied.

However, from interviews was concluded that the PoR doesn't consider these windows separately. These two types of windows are merged into one tidal window. The tidal window is often located at the entrance of a port basin. These tidal windows are based on experience. HCC and pilots know from experience with which currents they can safely manoeuvre into a basin. Subsequently, these tidal windows are chosen in such a way that there is enough water depth available along the trajectory.

How can accessibility as a function of the maintained bed level be assessed in a port-network? (a) What approach is required?

Ultimately, designing MBL's revolves around available and required water depths. In ports influenced by tides and/or river discharge, available water depths can vary in time and space. The required water depth varies in space. Therefore, a systemic-view of a port-network is required for the vertical design of channels.

In discrete mathematics, a network is called a graph. A graph is a structure which consists of a set of objects. With graph theory, a graph (mathematical structure) is used to model relations between objects. With a graph, a systemic-view of a port can be obtained, and a network (of channels) can be analysed. By considering available and required water depths in channels, a method to determine MBL's in a port-network has been framed. By looping over the MBL, corresponding accessibility percentages can be calculated. As a result, it becomes possible to maintain bed levels for neither too little (bottlenecks) nor too much (unnecessary dredging costs) water depth.

This design approach requires: a port-network, vessel- and channel properties, and local conditions (data). A computer model is subsequently needed to quantify accessibility percentages as a function of the MBL.

How can accessibility as a function of the maintained bed level be assessed in a port-network? (b) How can this be modelled?

The MBL model has a general set up; it can be applied to ports all over the world. In the tool, a network of routes can be created by using general latitude and longitude coordinates. These locations are projected in space with the 'pyproj' Python-module. The 'Shapely' - module is subsequently used to link these sections and to create a path. Next, the Python NetworkX-package is used to convert the paths to a NetworkX graph object. This package is designed to research the structure and dynamics of computational networks [Hagberg et al., 2008]. Properties (of vessels and channels), local policies and conditions (data), can be assigned to the network. With the Dijkstra's algorithm from the NetworkX package, distances and durations within the network can be calculated (geodetic calculations). Moreover, to handle dates and times in a general way, the 'DateTime' Python-module has been used. Dates and times are converted to a timestamp (number) and stored in a database. A Unix timestamp is the number of seconds between a particular date and January 1, 1970, at UTC.

With methods, the same calculations (such as analysing available and required water depths) can be performed on the entire network. The tool scans for tidal windows and determines whether to design for tide-bound vessels or not.

To what extent can a statement be made, based on traffic data, on how often the available water depth is used?

From the traffic study, it was concluded that there can be a significant discrepancy between actual and design vessel draughts. For example, only <0.1% of the largest container vessels (16-17m vessel design draught) handled in the *Prinses Amaliahaven* (almost) reach the draught for which channels has been designed (17m). In addition, less than 20% of these container vessels

achieve an actual draught of 15m. Also, the draught for which channels have been designed in the *Mississippihaven* (22.6m), was last (almost) reached in January 2016. The largest draught that has been reached since May 2016 is 4m below the design draught (18.6m). Based on interviews (A.3), the following could be concluded: if shipping lines would better coordinate their expected actual draughts with a terminal for a certain period, a win-win opportunity arises for port authority, terminal and shipping company because dredging costs can be saved.
Moreover, the liquid bulk terminal case (*3e Petroleumhaven*) provided the insight that other factors may also play a role as to why not all depth is used. Vessels on the *Nieuwe Waterweg* are allowed to sail with a maximum draught of 15m, while the vessel's design draught equals 17m. This is because the *Nieuwe Waterweg* cannot be deepened further due to the national interest in limiting salt intrusion [Interviews Port of Rotterdam, 2019-2020]. Also, further deepening is limited by the concrete foundation of the *Maeslantkering* (storm surge barrier). A *Maeslantkering* bottleneck analysis was performed in Section 4.5.1.

What observations can be made for the Port of Rotterdam (case study)?

Specific recommendations can be made for each case. These are also described in detail in Section 4.5. The model has shown that for the current MBL's, accessibility percentages can differ over a trajectory. Hence, there are bottlenecks in routes. For example; by dredging only 10cm extra between km notation 14-21km, the accessibility of the entire *3e Petroleumhaven* trajectory increases from 94% to 98%. With the recommendations of the model, the accessibility percentage over a trajectory can be aligned. This does not even necessarily mean that more dredging is required. In fact, By revising the MBL's for the 'city' and 'container' case, less net dredging is required, and the accessibility can be increased.
Moreover, some current MBL's are not logical at all. On the same route, it sometimes seems as if fairway- and basin channels are designed for a different draught than the berth (dry bulk and city case). Channels are no longer used for the draughts they have once been designed for. By maintaining channels for more actual vessel draughts, significant dredging activities (and hence costs) can be saved. For the 'dry bulk' case, this amounts to even more than 7 million m^3 of dredging volume. Also, the vertical design of the *2e Maasvlakte* is not consistent with PoR's design approach. Changes in the UKC policy are not reflected in the vertical design. In addition, the *Rottepeil* (-0.65m NAP) in the city centre of Rotterdam was used as the reference level. The *2e Maasvlakte* is approximately 40km located from the city centre. A normative low water level of -1.10m NAP should have been applied. So even by using PoR's own design standards, instead of the model, suggestions for improvement can be made. Overall, it can be concluded that the accessibility and use of existing channels should be reviewed on a regular basis.
A final recommendation would be to specify an outbound vessel draught for which channels are designed. Ports tend to pay more attention to inbound vessels and less to outbound vessels when designing channels. This is because inbound vessels are often normative for the vertical design. However, this is not always the case (for more export-oriented ports). Also, this difference may be due to the more complex nature of outbound vessels. Figure 2.2 also showed that in- and outbound vessels can encounter different water levels. The model can provide support to specify outbound vessel draughts and has also demonstrated this.

At last, the research question of this thesis can be answered:

"How can available water depths in a port-network be used more efficiently, considering maintained bottom levels, underkeel clearance policies and actual vessel draughts, for a Port of Rotterdam case study?"

In this study, a new, more detailed vertical design approach has been framed. Ultimately, the vertical design of channels revolves around available and required water depths. Since parameters to determine these depths vary in time and space, a systemic-view is required to design for the same accessibility percentage along a route. In this research, a general method to quantify accessibility percentages as a function of the MBL in a port-network has been framed. By looping over the MBL, corresponding accessibility percentages can be calculated. As a result, it becomes possible to maintain bed levels for neither too little (bottlenecks) nor too much (unnecessary dredging costs) available water depth. For this approach, a computer model is required. During this research, such a computer model has been developed. This model allows a port authority to be more rational about where to maintain for which bed level.

From the traffic study in this thesis can be concluded that for some channels in ports, there is a structural discrepancy between draughts for which channels have been designed and actual vessel draughts. Hence, there are structural over-depths. The draught for which channels have been designed should be reviewed on a regular basis.

Moreover, due to the different perspectives on UKC policy by shipping liner and port authority, the available water depth is not fully utilised. Shipping liners apply extra (unnecessary) margins for safe navigation. This could be overcome if a port would have an IMO-certificate for standardised best industry practices (for designing channels, acquiring local data and making forecasts). Such a certificate does not exist yet but could help the industry move forward.

6.2 Recommendations

Sedimentation rate and relation to the MBL

If the bed level comes closer to the morphological equilibrium, it is in theory expected that the sedimentation rate could decrease. However, the sedimentation process is so dynamic (due to weather, tides, currents, water density and shipping) that this is not measurable [Interviews Port of Rotterdam, 2019-2020]. This would be a recommendation for further research. If less dredging is not only a one-off profit, but also a structural one, this can affect the business case on which MBL to facilitate.

Economic study

An economic study to assess the impact of adjusting the MBL could help a port authority to be even more rational about where to maintain for which bed level. The impact on port-income by increasing or decreasing the MBL, and related maintenance costs, would have to be studied. An economic study has to be performed. Subsequently, the MBL model could provide support with an economic assessment. Dredging volumes only need to be converted to costs. Also, port-income can be linked to the MBL's and assigned to routes. Finally, with additional methods in the model, the economic study could be performed.

Seasonal water level variations

In the PoR, there is a seasonal variance in water levels. There are different available water depths per season. This is due to river discharge and wind. The data-set used for this study is too small to draw conclusions in this field. However, it would be a recommendation for further research. If the seasonal difference in water levels is significant, the maximum draught for channels could differ per season.

Underkeel Clearance policy

In the PoR, deterministic UKC calculations are based on generalised experiences from the past, which have been converted into a fixed vertical safety margin under all hydro-meteo and tidal conditions. Dynamic UKC calculations are based on live measurements data and predictions from validated models. This is currently only applied in the port approach channel. In good and calm weather, this results in a smaller UKC than the deterministic UKC calculation. In bad weather, the dynamic UKC calculation will result in a larger and safer UKC than the deterministic one. If it becomes possible in the future to collect live local data (water density, water level, wind speeds, currents, waves) throughout the port, this policy may be applied throughout the port. It will become possible to provide (live) DUKC advice and predictions. Channel- and vessel-specific formulas will have to be applied to determine the DUKC. However, it is also important to have a transparent UKC policy that can be explained to clients. DUKC policies tend to be very complex (black box) which captains do not like because they can not see if they meet their company policy. Also, conditions in the port are much more gentle than in the approach channel, so the advantages of a DUKC policy in a port would be smaller.

Moreover, an interesting finding was made during an interview with a pilot. When sailing through confined channels (in a relatively small port basin), "it feels like putting a cork back into a wine bottle". Water is pushed out of the basin when sailing through the confined channels, especially when more vessels are moored in the basin. The return flow negatively affects the controllability of the vessel. This effect is not included in existing UKC build-ups and policies. It would be interesting to do further research on this. To map these effects, it would be recommended to perform live measurements. Perhaps, a certain UKC policy should be applied for a certain vessel-class to channel surface ratio.

Parametric fitting of accessibility curves in MBL model

The MBL model analyses water levels in discrete steps. With a parametric fitting of an inverse logistic distribution, the fit can become continuous. In practice, 100% accessibility does not exist. There is always a chance that a lower water level than the current lowest water level will occur. With a continuous fit, there is extrapolated to high and low water levels. With such an approach, it becomes possible to make an accessibility curve with four values: an average value, standard deviation, skewness and kurtosis (a measure of the "tailedness"). This could be a further extension of the computer model.

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A Interviews

Concise summaries of the most interesting findings in the interviews are presented in this Appendix. The conversations were dialogues. The interviews helped to provide (historical) context and a practical point of view regarding the discussed topics; to obtain a realistic scope and to give findings of this research the potential to be implemented.

The summaries were typed by the author of this report, Sander de Jong, interviewees cannot be held responsible for the statements made.

The interviews are in order of the last names of the interviewees.

A.1 Port of Rotterdam interviews

N. Van de Burgt
Employer: Port of Rotterdam
Description: Part of the Business Analyse Intelligence (BAI)-team

Date: 29/11/2019
Subject: Port income and waiting costs
Location: World Port Center

The BAI-team consists of 2 strategists (who are following developments), 3 intelligence advisors (experts in dry bulk, liquid bulk and containers, who know the customers and destinations) and 3 data scientists (making models, financial forecasts and scenarios). N. guides the data scientists and is responsible for port dues.
Vessels berthing at the PoR pay port dues, which is used for maintaining the waterways (dredging) and quays. The total PoR income consists of port dues and hiring of terminals. The port dues are composed of a vessel-part and throughput-part. The larger a vessel (in gross tonnage m^3), the more it has to pay, because it uses more depth and has a larger impact on the quays. Also, the more cargo a vessel transfers at a terminal, the more port dues it has to pay. There isn't a direct relation between vessel waiting times and port dues, the PoR doesn't compensate a vessel if it has to wait outside the port or at a berth due to dredging maintenance works or low water levels for example. There is only a direct relation if a vessel decides to go to another port instead of the PoR (client loss). For a vessel, waiting time is very costly due to fuel, chartering, crew, demurrage costs and costs of opportunity. So the PoR wants to prevent this as much as possible from happening to keep clients satisfied and prevent reputational damage.

T. Cleerdin
Employer: Port of Rotterdam
Description: Duty officer Harbor Coordination Centre (HCC)

Date: 08-01-2020
Subject: Accessibility in practice at the HCC
Location: World Port Center

HCC is an operational department, they don't determine the depths of the waterways. HCC uses a document called 'Guidelines for tidal vessels'. These guidelines for tidal vessels are based on agreements between the Operational Service of the Rotterdam-Rijnmond Pilotage Corporation (LRR) and the Port Coordination Center / vesselping Traffic Management department (HCC) of the Port of Rotterdam Authority. These agreements serve to outline the conditions under which pilotage (in Dutch:*loodsen*) of sea vessels can take place.

The process is approximately as follows: an agent reports a vessel in 'portbase', HCC receives a notification from an agent about this vessel, which ends up in 'HaMis'. This system indicates if there is a (risk of) vertical and/or horizontal tidal gates for the vessel, based on the 'Guidelines for tidal vessels'. If there is a risk, HCC assesses this within 24 hours (the agent also receives a message if the vessel is tide-bound to contact HCC).

Starting with the vertical tidal window, HCC examines the route of the vessel. When a vessel is calling 36 hours in advance at the port, they look up the lowest height of tide in the next 2-3 tides according to NAIADE. Subsequently, they look at the measured bottom levels in 'portmaps' (maritime chart server) and also fill in the required UKC policies. So HCC determines whether there are critical points, based on the measured bottom levels, UKC and the lowest height of tide. In practice, if there is a critical point, there is almost always only one critical point for a vessel, where a certain height of tide is required to pass. If a vessel can pass this point, it can sail without further vertical restrictions to its destination. Most bottlenecks are known based on experience of the (assistant) duty officers, so they know where to search. The port entrance channel is very seldom the bottleneck in a route. HCC checks the required height of tide in order to meet the required depth at the critical point. In 'NAIADE' can be observed when this height of tide occurs (using the closest measurement point), a vertical tidal window when the vessel has to pass this critical point is determined. Subsequently, horizontal tidal restrictions are checked, using DTP-viewer (which is based on the 'Guidelines for tidal vessels') if the vessels arrives within 3 days. If longer, LTTP-viewer is applied, which is based more on astronomical predictions. The windows of the horizontal and vertical restrictions are overlapped creating a combined tidal window in which the vessel has to arrive at a critical point. The speed of the vessel and tidal wave are not considered individually, it is embedded in the guidelines. At last, there is recalculated (using 'Guidelines for tidal vessels') at what time a vessel has to pass the Lower Lights in order to safely navigate.

Some tidal windows are window-based and some are point-based. An example of the latter is for vessels sailing to or from the 3e Petroleumhaven, they have to arrive at 0,5kn while flood is decreasing. In practice, no one will feel the difference between 0.35 and 0.65 kn of power while sailing. In addition, sailing by the minute is also virtually impossible. The tide guidelines are also exactly as it says: guidelines. It is nice we can read and predict currents-rates and wind speeds on two decimal places, but that accuracy has little to say in the "real world". In general, the rule of thumb at the HCC is to not count yourself rich. We stand for safety. I can agree with a window around a point-based tidal window of + -30%. Usually the time difference between 0.65 and 0.35 kn is also so small that there are not really shocking findings leading to another tidal window (accessibility moment). I do interpolate a bit if there are 20-30 minutes between them, so for example:
14:00 - Current 0.65 kn
14:30 - Current 0.35 kn
Tidal window advice open: 14:15

W. Hoebee
Employer: Port of Rotterdam
Description: Manager Division Harbor Master of Rotterdam

Date: 02/12/2019
Subject: Maintained depth design formulas
Location: World Port Center

The formulas that are currently used to design the maintained depths of waterways in the PoR are approximately 8 years old (so approximately 2012). There is no documentation of this old design approach. The Rottepeil (NAP -0,65m) was used as a reference level. The maintained depth (NAP) was subsequently determined by subtracting the Rottepeil, normative vessel draught and UKC (which was 1 or 2 meters).

W. Janssen
Employer: Port of Rotterdam
Description: Advisor Hydro (& Wind) at Data Management

Date: 05/12/2019, 13/01/2020
Subject: Measured height of tide
Location: World Port Center

RWS and PoR have their own measurement-points in the PoR area. *Hoek van Holland* (HvH) is an important measurement-point because it is at the entrance of the port. HvH is a RWS measurement-point, but the PoR has started measuring at HvH as well since one year approximately. These measurements aren't very consistent unfortunately because of a new system that was installed in this year. Other measurement points of the PoR provide better data. RWS's data can be requested online.
Moreover, PoR measurements-points are placed in such a way that the measured heights of tides can be interpolated linearly. The 'OSR-model' can also provide measured/predicted water levels at any location at any time, but that requires quite a lot of computation time. Only the output of the OSR model as shown in NAIADE is saved. To generate output at other locations, we sometimes run a hind-cast sum, but then for a specific weather event. Not for a whole year, for example. In 'NAIADE': H10 are measured water levels at measurement points and PH10 (P=predicted) are points in the OSR-model, from which data has been extracted and stored. The results of PH10 and H10 are almost identical.

N. Van Klaveren
Employer: Port of Rotterdam
Description: Business manager (EMO terminal)

Date: 13/07/2020
Subject: Actual draught EMO terminal
Location: Online

The MBL in channels to the *Mississippihaven* have been designed to allow vessels with a draught of 22.6m. This was designed (for valamax vessels) as such in a time when China placed a trade restriction on Brazil. These vessels came to the PoR instead of China during this trade restriction. Since 2016, this restriction has been lifted and these vessels are sailing directly from Brazil to China again. The chance that these vessels will come back is not that great. There are other developments, however. There is a 'project artic mining' in Antarctica to further expand an ore mine. The capacity is currently limited, but it is being expanded. These vessels would be capesize; these vessels do not have a larger draught than current vessels visiting this terminal (panamax). Traffic data showed that the draught for which the channels were designed (22.6m) was last (almost) reached in January 2016. The largest actual draught that has been reached since May 2016 is approx. 4m below the design draught (18.6m). The terminal has not adjusted their contract to a different depth. This is also because EMO is in a competitive market, they want to be accessible for every vessel that calls at the terminal. However, this is good feedback. EMO pays for a depth that they have not used in recent years.

P. Nordbeck
Employer: Port of Rotterdam
Description: Nautical advisor at DHMR

Date: 08/12/2019
Subject: Deepening of Nieuwe Waterweg & Botlek
Location: World Port Center

The Botlek wasn't deepened just because a client (Koole and Vopak) requested it. It has been an investment of the PoR in collaboration with the Dutch government (RWS) to attract more vessels to Rotterdam, which increases employment opportunities. It is a special case. The increased maintenance costs are larger than the increased port income due to the increased vessel sizes. It is actually deepened for one new normative vessel. The new waterway's design draught is 15m, while this vessel can actually load till 17m draught. It unloads till 15m draught near the Maasvlakte and then sails to the Botlek. The client would obviously prefer to be able to sail to the Botlek with 17m draught, but that would be too expensive for the port authority. So they have agreed to a depth of 15m. Moreover, further deepening is limited due to the concrete foundation of the *Maeslantkering* (storm surge barrier). A vessel draught of 16m might be possible some day. Moreover, it would be interesting to know how much dredging costs are saved annually by facilitating those vessels on the *Maasvlakte* instead of at the Botlek (more inland), and after how many years the required investment would be earned back.

Date: 10/06/2020
Subject: Tidal window 3e Petroleumhaven
Location: World Port Center

For this port basin the following tidal window is in effect for the largest vessels: vessels have to arrive at *Scheurkade* while 0.5kn flood-currents are decreasing. *Scheurkade* is approx. 1.5km in front (observed from sea to berth route) of the port basin. This is a great example of an experience based tidal window. Pilots know that with these currents, they will have the correct stream rate (approx. zero) to manoeuvre into the port basin as soon as they arrive there. In fact, they even know that at the beginning of their route at *Hoek van Holland* (16 km away), they will not be bothered too much by currents.

B. Van Scherpenzeel
Employer: Port of Rotterdam
Description: Worked as a captain. Currently, program/project manager Division Harbor Master of Rotterdam

Date: 05/12/2019
Subject: Water depth & Underkeel Clearance policy
Location: World Port Center

Ben has experience discussing the perspective of a PoR client (a large oil company) on the UKC. Port authorities and shipping liners have their own point of view on what factors to consider to determine the UKC. Clients often add variable factors to the opposed minimum required UKC by a port authority. The values of the factors vary per port and depend on the reliability and degree of uncertainty of each factor in a port. Also, container vessels, for example, have tight schedules, so they do not want to have to wait for higher water and can choose to sail with a safer UKC margin.

To make clients load more till a larger draught (more cargo), without increasing dredging activities, can be achieved by increasing the data quality and transparency of factors that influence the UKC-policy of a vessel (like measured water levels, depths, tides and water density). This reduces the margins clients are applying as they enter a port with more confidence. Moreover, the draught a vessel loads to also depends on the other ports a vessel is visiting, as the margins vary per port and some ports may be normative. It would be a good idea to regulate ports and waterways with some kind of IMO-certificate for example. This certificate would guarantee best industry practices and would give clients more confidence to apply smaller UKC margins and increase draught.

Moreover, a terminal can apply to the port authority for extra depth (bed level) to receive larger vessels. However, this is not always possible. The quay wall must be able to handle this. Also, on the *Nieuwe Waterweg*,for example, plays a national interest. This can not be deepened further to limit salt intrusion. This is undesirable for the agricultural sector.

Date: 20/08/2020
Subject: Actual vessel draught
Location: Online

Moreover, actual vessel draughts are determined by a computer in the vessel. Just before a vessel is about to depart, so when it is fully loaded, the actual draught is calculated. This is the statical draught measured at berth. This is also converted to the statical draught in salt water. Local water density is required input. The local water density can be measured, but sometimes just an assumption is made. The calculated draught is compared to the Plimsoll mark for checking. Subsequently, the computer can calculate and predict, based on expected fuel and fresh water (by crew) consumption, what actual draughts will be. When calling at a port, the most recent actual draught is communicated (converted to salt water and statical).

R. Seignette
Employer: Port of Rotterdam
Description: Engaged in research, visioning, strategy development, policymaking and strategic advice in all maritime matters related to maritime transport; in particular vessel traffic management, information management and port development; National and international

Date: 09/10/2019
Subject: UKC-policy in the PoR
Location: World Port Center

The UKC-policy in the PoR is based on the sailing experiences of pilots (*loodsen*) and captains in the port. It is very difficult to base the UKC-policy on calculations, amongst others because the waterways aren't perfectly-shaped rectangles. This influences the squat of a vessel considerably. Currently, a vessel reduces speed and hence squat-effects to navigate more safely. Moreover, the UKC influences the manoeuvrability of a vessel.
An echo-sensor is often placed at the bow of a vessel to measure the depth, while the critical depth is often at the stern of a vessel. The reason for not placing the sensor at the stern is because it gives unusable measurements due to air bubbles induced by the vessels speed and motor. Sensors at the bow do not correct for dynamic effects to measure the critical depth at the stern. Therefore exact critical depths aren't live-tracked on a vessel's route. The sensors at the bow are used to provide an indication of the depth. Moreover, the sensor at the bow is used to measures the gradients in depth, which can alarm the captain to prevent from getting stuck. If depth decreases rapidly, it must be noticed as soon as possible, therefore the sensors are placed at the bow.

Date: 13/01/2020
Subject: Costs & benefits of adjusting the maintained depth
Location: World Port Center

The PoR had had an extensive traffic study performed by RIGO Research en Advies BV [2009], to try to quantify the economic damage if the *Maasgeul* would not be deepened. It now turns out that, despite the extensive research, there were still some errors in the forecasts, for example there was expected that the amount of vessels would increase, but that didn't happen, vessel sizes increased. As for increasing or decreasing the maintained depths of waterways, it is almost impossible to asses the economic impact. The costs for businesses, if the accessibility of a berth is reduced for example, cannot be overseen. The economic discussion is not rational. Everyone is used to the current depths, has adjusted to it and counts on it for its business operations. Even if there are over-depths, a customer expects that he can receive a large vessel if he wants to. Moreover, it is hard to compare the costs and benefits, because the benefits (of less dredging) are for the port authority and the costs (of increased waiting times or sailing with less draught) are for the business community. It isn't the same balance. So it would be smart to make the assumption that the current safe and smooth accessibility of berths should not decrease to not damage businesses. It is still interesting to investigate the structural over-depths of waterways to reduce dredging costs for the port authority.

J. Sonnenschein
Employer: Port of Rotterdam
Description: Dredging manager at the AM department

Date: 09/12/2019
Subject: Customer, dredging policy, practice and dredging-decision-model
Location: World Port Center

Customer
A client for DHMR is a vessel (stakeholder; captain on board and agent), for the AM-department it is the holder of the berth-contract (a commercial business, vesselping company, terminal or whoever has a contract). The contract-holder who pays for the depth is the customer for the AM-department, the contracts determine how the maintenance is organised, whether a vessel is coming or not.

Dredging policy & trends
The dredging policy is to ensure that all contractual/maintained depths are available, and dredging + 0.5m. Sometimes a customer exceeds the contract depth and they are allowed to use this maintenance margin (for an additional tax) because there has just been dredged, but when they come back next time they can't assume this depth is available again (no rights can be derived from it). Dredging is becoming more and more expensive because margins are increasingly being reduced. In the past, there didn't have to be dredged for 6 weeks after maintenance dredging took place. Now, more often less dredging has to take place because the UKC-margins are getting smaller (primarily a trend in the container business). The sedimentation is not even, it sticks at specific places. More often but less dredging is very costly due to high initial mobilization costs of dredging vessels.

If a captain thinks it has hit the bottom, the chartered vessel is contractually obliged to have it checked for damage by a diver (which he must order) or worst case in the dock. PoR must pay if there is damage because there wasn't enough depth available. It can be that a vessel has hit the bottom in another port so that the damage was already there. Therefore we want to make sure the maintained depths are maintained to avoid these kind of damage-claims.

The MD of a waterway is guaranteed by RWS and the port authority, making sure it is available for vessels at all time. So clients pay the port authority to facilitate this MD. To reduce dredging activities, dredgers often over-dredge. This means that the actual bottom level can be below this guaranteed depth (MD). On the other side, the design draught isn't always reached in practice because vessels are not always fully loaded. Therefore, the available water depth can often be larger than required in practice. The port is aware of this fact and has less priority to have waterways dredged where mainly vessels visit with draughts smaller than the design draught. The water depth can become smaller than the guaranteed depth (MD) in this case (under-dredging). Now, this decision to dredge less and have a smaller priority to comply with the MD in certain waterways is based on the experience of dredgers and is not based on data or calculations. If a vessel with a large/design draught announces itself (which is at least 24 hours in advance) and the MD isn't available, urgent dredging must take place to comply with the MD. Urgent dredging is more costly than normal maintenance dredging.

Dredging-decision-model

The PoR is developing a model to support the decision making process of prioritizing the dredging maintenance of areas in the port. It is a static model that doesn't consider varying vessels, water levels or water density gradients. It only considers contractual depths (MD). For every route in the port (from sea to berth) is mapped where the passageway is minimal. This is determined for each route and the results are overlaid to identify low and high priority dredging maintenance areas. The model is expected to be finished in February 2020.

Potential for vessels measuring depths themselves and sharing data?
A vessel is often equipped with a sensor to measure the depth from keel to bottom. Inland vessels do this all the time and share their data with each other. They have to decide how much cargo they can take with them when (un)loading. Sea-going vessels don't share their data because their measurement-sensors do not give accurate results (see also interview with R. Seignette). The sensors don't correct for tides and changes in water density, which is required to measure accurately. Inland vessels don't have to deal with these problems. Normal vessels have a single beam measurement device, surveying vessels in the port have a multi-beam and can take the previously mentioned factors into account; making them much more accurate. So it is not possible to use the sea-going vessels' data and dispose the survey boats. The data could be used, for example, to have an indication of where shallows are located to utilize the surveying boats more efficiently.

A.2 Royal HaskoningDHV interviews

J. Helbing
Employer: Royal HaskoningDHV
Description: Ocean shipping consultant. Jolke worked at Maersk for 20 years and has now been a due diligence consultant for 10 years.

Date: 10/06/2020
Subject: Economical impact of adjusting the bed level
Location: Online

The market is the driver, what clients want is what the port facilitates. The required bed level can also depend on the market position of a port. If you are always in the middle of a market/rotation, vessels will never be completely fully loaded. If you are an end-to-end port, a vessel is fully used for your port and you can therefore expect more draught. Also, containers from Asia are generally lighter than containers leaving from Europe. Even though both vessels are fully loaded.
The market is not always rational. You could link an economic impact assessment to market shares. However, this would be more of an econometric study. Furthermore, to optimise bed levels, you could compare the costs of waiting time against dredging costs. It cannot be fully compared because waiting times are costs for vessels is, and dredging costs for a port authority, but it is a starting point. Benefits can be divided. And maybe there are no benefits, then you don't need to have this discussion at all.

J. Lansen
Employer: Royal HaskoningDHV
Description: Project Manager Maritime and Waterways

Date: 31/07/2020
Subject: PIANC guidelines
Location: Online

When designing channels, we often use PIANC guidelines in projects. These guidelines are designed to facilitate safe navigation. The idea is that they can be used everywhere. Because they are so general, the results are often conservative.

J. Valstar
Employer: Royal HaskoningDHV
Description: Maritime consultant

Date: 08/06/2020
Subject: Underkeel Clearance policy
Location: Online

UKC policy sometimes seems like a subjective topic. One finds 10 cm safe and the other one meter. It also varies per vessel and type of cargo. Tricky topic. UKC influences the risk of contact with the bottom, the maneuverability of a vessel, the risk of damage and the chance of a port being blocked. A port takes responsibility and a risk with their UKC policy. That would make it understandable if they are on the conservative side. If a vessel gets stuck in a port and a temporary closure occurs, the economical damage can become enormous. Also, the whole insurance aspect of maritime vesselping is involved. From a practical and commercial point of view, RHDHV does not often recommend tight UKC policies in their projects. That's not worth the risk. Moreover, the required UKC is strongly related to a location and situation. Therefore, the determination will likely always remain a local and hands-on experience. Also, the UKC is strongly related to vessel speed.

With regard to developments in this area, a Dynamic UKC policy is sometimes applied for approach channels. This Port of Rotterdam uses this for example. OMC-DUKC is called the software of a company that Jacco has heard of. This was developed in Australia for a bulk port where the same vessels are often handled. They have ten berths for all the same bulk carriers. They have had the opportunity to monitor the behavior of these vessels in detail in different conditions. They are now trying to sell those results and software to other ports. Jacco doubts its usefulness and effectiveness because it is of interest to only 1% of the vessels.

G. Vaz
Employer: Royal HaskoningDHV
Description: Nautical expert (former captain)

Date: 04/06/2020
Subject: Underkeel Clearance policy
Location: Online

Gary sailed himself, he was a captain, so he has a lot of practical knowledge. When sailing, a captain takes interests of the charterer, vesselping owner and crew safety into account. So when it comes to UKC policy, a captain doesn't take sides if there are different ideas, he manages it. A captain can always go against charterer's wishes to put safety first.

UKC policy and enough water depth remains a recurring challenge, in large and small ports. It is a difficult and dynamic topic. vesselping companies and port authorities can have a different perspective on UKC policy. In practice, only a pilot has local knowledge. A captain doesn't have the same information about water depths, local conditions (wind, waves, currents, recent rainfall/drought), water density etc. Only when a pilot comes on board, it is known with which UKC there we will be sailed. For a vessel's load planning, it would be helpful if ports would disclose their UKC policies for varying conditions. This would help a charterer to decide which draught to load, based on forecasted conditions.

A.3 Ship liner & Terminal interviews

L. Bignotti
Employer: Koole Terminals
Description: Operations manager Koole Botlek Terminal (*3e Petroleumhaven*)

Date: 03/08/2020
Subject: Accessibility and adjusting the maintained bed level
Location: Online

Koole has greatly benefited from the deepening of the *Nieuwe Waterweg*, but this was not the reason for the project. It was to remain competitive as a port in general (compared to Antwerp). At our liquid bulk terminal in the *3e Petroleumhaven*, the berth pocket is a little deeper than necessary to avoid getting stuck when the tide decreases. In recent years, they have not experienced that their terminal was not accessible for a vessel.
A figure with accessibility percentages as a function of the maintained bed level was presented to the interviewee. From this it is concluded that they would most likely not opt for a lower accessibility percentage, even if this saves lease fees (due to dredging savings from the port authority). A vessel cannot be planned on a specific date. If a vessel arrives at the port and cannot enter, it will cost the charterer about €35.000,- per day (for this 15m draught vessel class). This causes too much damage to a customer's business case. On the terminal side, there is also well in advance ensured that everything is ready to handle the vessel. Surprises regarding accessibility would also mess up the operational planning.

K. Patnaik & E. Idzinga
Employer: Maersk line (and former APM Terminal manager)
Description: K. Patnaik is a Marine Planning manager. E. Idzinga is a Port Captain at Maersk line. Previously, he worked as Shift Manager Operations at APM Terminals.

Date: 18/06/2020
Subject: Water depth; draught and UKC policy
Location: Online

Maersk's UKC policy
The guidelines are discrete. But Maersk has a standard UKC policy. It is usually based on vessel size, type of sea bed and port section. They have a port memo for every port, which contains information about the port infrastructure and people (actors) they can contact. The master (captain) uses this to have full understanding of what to except.

How critically do you view the UKC policy of the Port of Rotterdam?
Maersk company policy is almost always exceeding the requirements of a particular port. Although less UKC may sometimes be allowed, Maersk is absolutely on the conservative side of UKC policy. To see how much cargo a vessel can take, the actual summer draught on the Plimsoll mark of a vessel's hull is used. As long as we are maintaining the Plimsoll mark, we are good. The maximum draught of a vessel is different than the summer draught on the Plimsoll mark. Moreover, the weight of cargo (to determine draught) is based on what the owners/customers pass on. They need a VGM (Verified Gross Mass) load certificate. Furthermore, the pilot at a port is an assistance to the master. The master is responsible and makes final decisions. The master overrules a pilot in case of discussion. So no, we never blindly follow the UKC policy of a port.

About the recent record in terms of draught (17.3m) in the Prinses Amaliahaven, which considerations underlie this? Do you find that risky or not? Why not 17.5m for example?
The vessel was loaded to the best of our ability, and again, summer draught was kept in mind. There was more than sufficient water depth available, UKC violation was not a discussion. It was not that there were good conditions or anything like that, it was purely to do with business.

How do you analyse water- and bed level data? In relation to planning/routing
The Avanti tool from the Port of Rotterdam (see Section 2.2.2) was used. It is now offline, but a newer version will be released in September. Maersk is satisfied with this because they like to use it. Moreover, predictions are more valuable than live data to Maersk. Uncertainties are in

the nature of business, a lot conditions can change, that is always kept in mind. If water level reduces for example, there is so called optional-cargo removed in one port before going to next. Furthermore, Water density changes slightly with high and low water, it may also change due to the wind direction. The minimum water density in basin that we have seen (measured) in long period is used. If there would be more data available regarding local conditions and bed levels, Maersk would consider to load probably 20-30cm more.

APMT related: Do you pay the port for the facilitated bed levels towards your terminal?
It is included in the lease fee. Terminals pay for the berthing pocket. The costs increase per 10 cm bed level.

APMT related: 'Results of the traffic study were presented', is it worth it to always be able to receive the largest vessels even if these are less than 0.1% of the total number of vessels??
We haven't looked at it that way yet. Everything is built for the future. Maybe you don't need all that water right now. From experience, there seems to be little interaction between terminals and shipping lines regarding discussing actual vessel draughts. Maybe it hasn't come to mind yet. Maybe a win-win opportunity arises if we can estimate how much depth we need (over the period) of this year. This could save maintenance dredging costs (which are in turn incorporated into fees/contracts). We will discuss this further internally.

A.4 Other interviews

A. Kärnebro
Employer: Port of Gothenburg (Sweden)
Description: Harbour Master

Date: 20/04/2020
Subject: Water depth policy
Location: Online

The port of Gothenburg is the largest port in the Scandinavian countries. There are mainly container- , ro-ro- , passengers- and liquid bulk terminals. The interesting thing about the Baltic region is that they have no/hardly any tidal influences, only mean sea level. The water level fluctuations are limited, also for waves. Water level data is not stored and there are no tidal windows. Depths in the port are measured with soundings. Maintenance dredging is only three to four times per year required.
Moreover, it is mentioned that the UKC policy in the port is old. It is a static policy and they want to include more dynamic factors in it. They have never had a discussion with Maersk regarding UKC policy. In the future, the port wants to provide UKC policies to vessels calling at the port, because it should be specific for every vessel.
There are no other ongoing research activities related to depth.

J. Van Rijsewijk
Employer: Loodswezen (pilotage corporation)
Description: Pilot

Date: 17/08/2020
Subject: Discussing model output & sailing experiences
Location: Online

Prinses Amaliahaven trajectory
The *2e Maasvlakte* was built for petro-chemical vessels and containers, but now it is only used for containers. There is indeed more than enough available water depth. This probably has to do with contractual agreements. Moreover, it is questionably whether maintaining for a higher bed level would be a one-off or structural gain due to a reduced sedimentation rate. It is remarkable

that for the same bed level is maintained throughout the *2e Maasvlakte*, even-though, for example, UKC policy changes.

3e Petroleumhaven trajectory
He has sailed this route four times with the largest vessel classes. The vessels have not visited this port basin much more often yet. From his experience, sailing into this port basin ”feels like putting a cork back into a wine bottle”. Water is pushed out of the basin by sailing through the confined channels, especially when more vessels are moored. The return flow negatively influences the controllability of the vessel. You have to sail carefully, especially not too fast. There are no problems on the *Nieuwe Waterweg*.

Waalhaven trajectory
The Waalhaven is larger, there is no problem here related to water pushing water out of the basin. He has no problems on this trajectory. However, it is illogical, now you mention it, that the berth is shallower than the surrounding channels. He does not understand why the port authority is doing this. It is true that you do not want a tidal window for these container terminals. Containers have tight schedules. That could have to do with it.

Mississippihaven trajectory
He does not sail this route. It is true that there is also more than enough available water depth there. In addition, 24/7 accessibility is less important for this type of cargo (dry bulk) than for containers.

B Technical background PoR

B.1 Depth and draught definitions

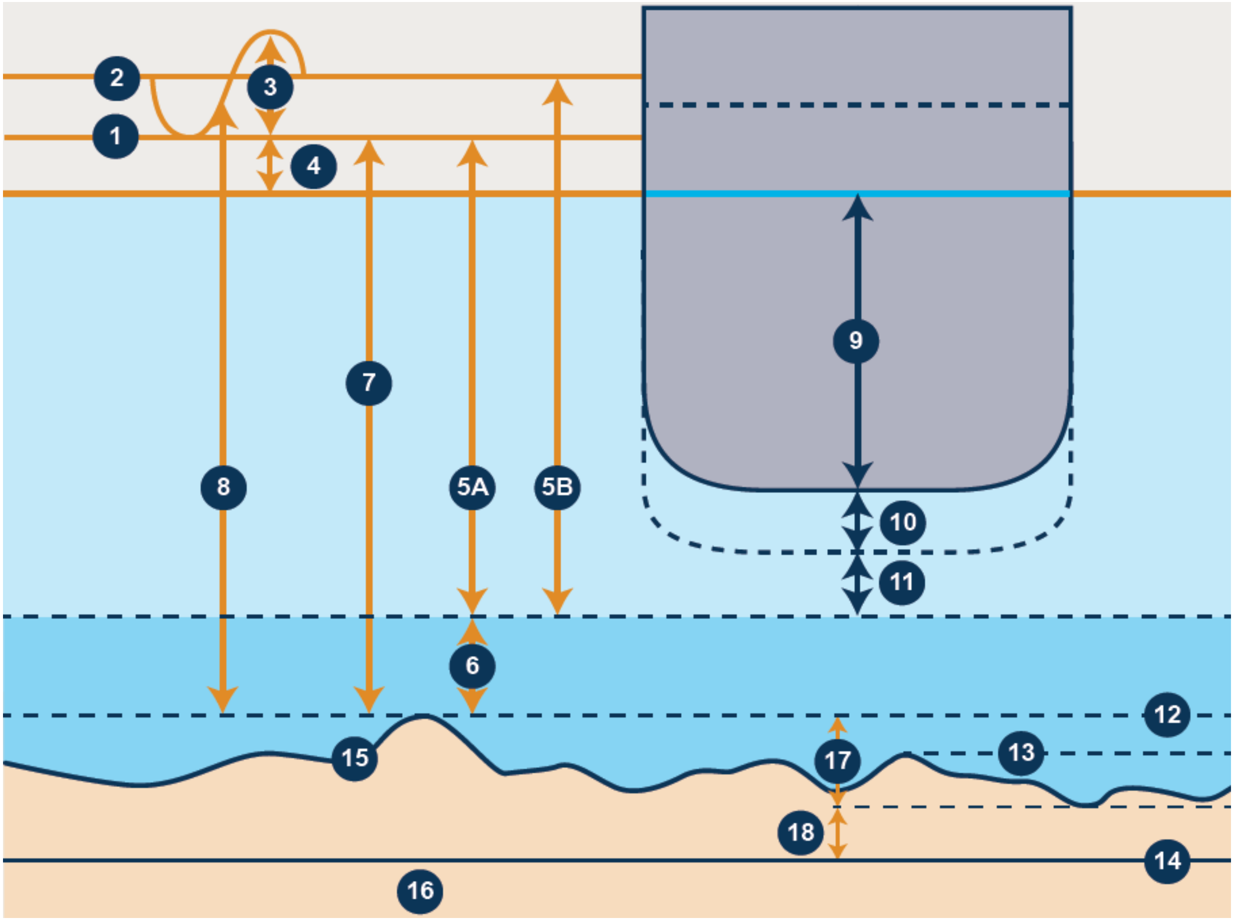


Figure B.1: Depth and draught definitions [Port of Rotterdam: DHMR, 2019]

1. **Chart Datum ALAT**: Approximately Lowest Astronomical Tide. A level so low that the tide will not frequently fall below it. It is the level below which soundings or maintained depths are given on charts. Chart datum is also the level to which tidal levels and predictions are referred

2. **Chart Datum NAP**: Normaal Amsterdams Peil. This is a mean sea-level (North Sea). Only used as Chart Datum in the Netherlands

3. **Height of the tide**: The vertical distance at any instant between sea level and chart datum

4. **Hydro-meteo effects**: An extra margin to reduce the number of water levels lower than ALAT to 1%

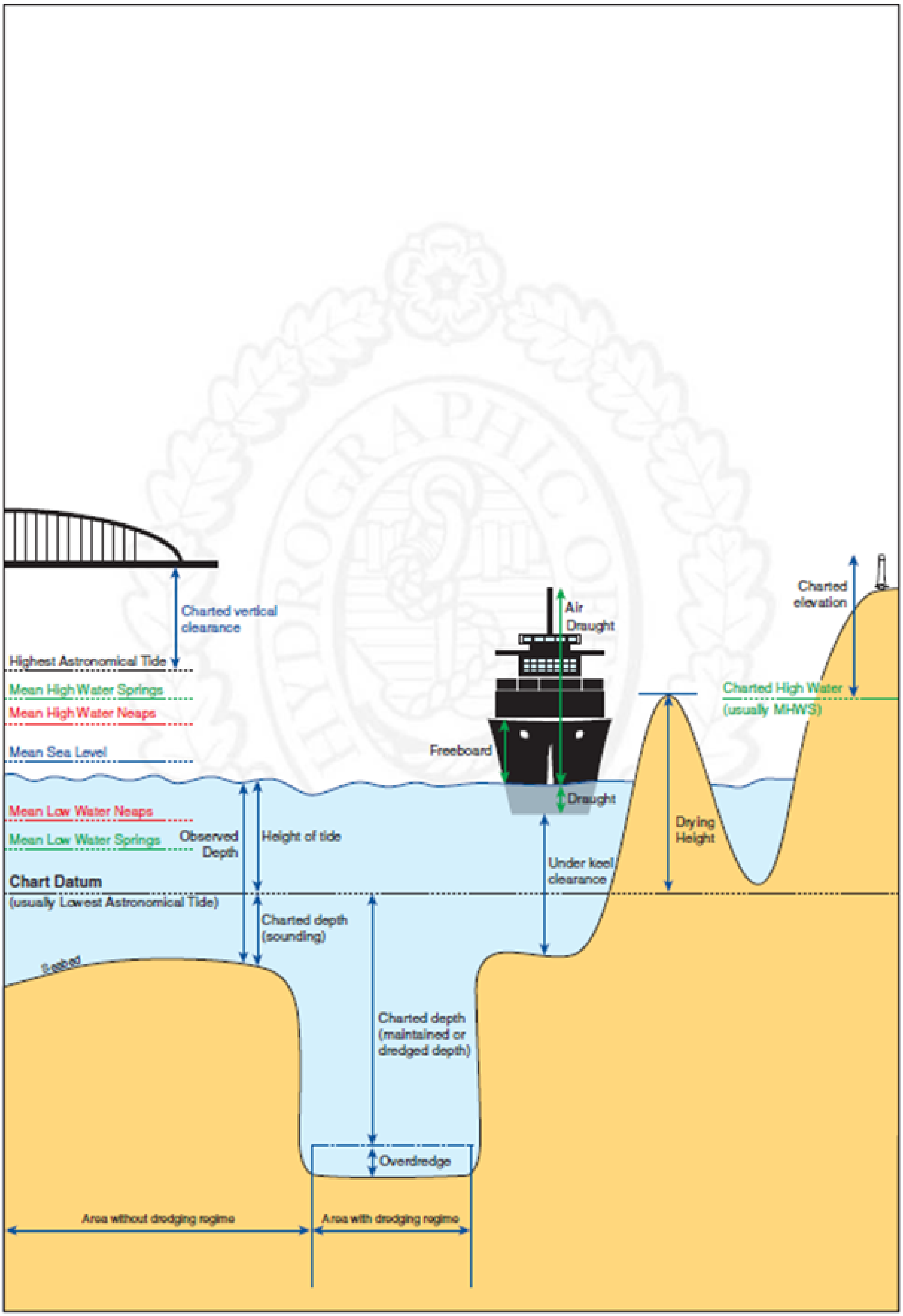
5. **Maintained depth**:

    (a) The maintained depth at which a channel is kept by human influence, usually by dredging. It is the minimum depth at the location through periodic sedimentation and dredging activities, relative to ALAT

    (b) Idem, relative to NAP

6. **Maintenance margin**: An additional depth margin provided by a dredging operation to ensure that the depth at a specific location is never less than the pre-determined maintained depth over the interval between programmed dredging operations
7. **Sounding**: Measured vertical distance between ALAT and actual bottom level during most recent sounding
8. **Observed depth**: The vertical distance from the sea surface to the actual bottom level, at a certain moment in time
9. **Static draught**: The depth of the keel below the waterline along the hull, measured in salt water ($1.025kg/m^3$)
10. **Fresh Water Allowance**: Extra draught due to difference between density of salt and fresh water
11. **Under Keel Clearance**: The difference between the draught of a vessel and the depth of water used in the design to calculate the nautical guaranteed depth for a berth
12. **Design bottom level**: Designed bottom level for new construction projects. This level is the upper limit regarding tolerances (”nothing above”)
13. **Average bottom level**: Average bottom level for new construction projects
14. **Construction depth**: Theoretical bottom level used for structural stability calculations
15. **Actual bottom level**: A varying pattern that varies with time, where the bottom actually lies. This is the level that follows from a survey
16. **Unstirred bottom**: Subsoil that has not been affected by the dredging work. Within the stability calculations for structures, it is possible that the original (undisturbed subsoil) soil properties are used
17. **Dredging execution tolerance**: With large dredging equipment it is not possible to deliver a completely flat surface at great depths. The method has an inaccuracy that depends on the type of equipment used
18. **Stirred bottom**: The top layer of soil that remains on the bottom after the dredging activity has not been left undisturbed but ”stirred”. This soil no longer has the original soil properties, which is relevant for the structural stability calculations

Employees of the PoR also often refer to the UK Hydrographic Office [2020]. This standardised depth terminology is presented in Figure B.2.

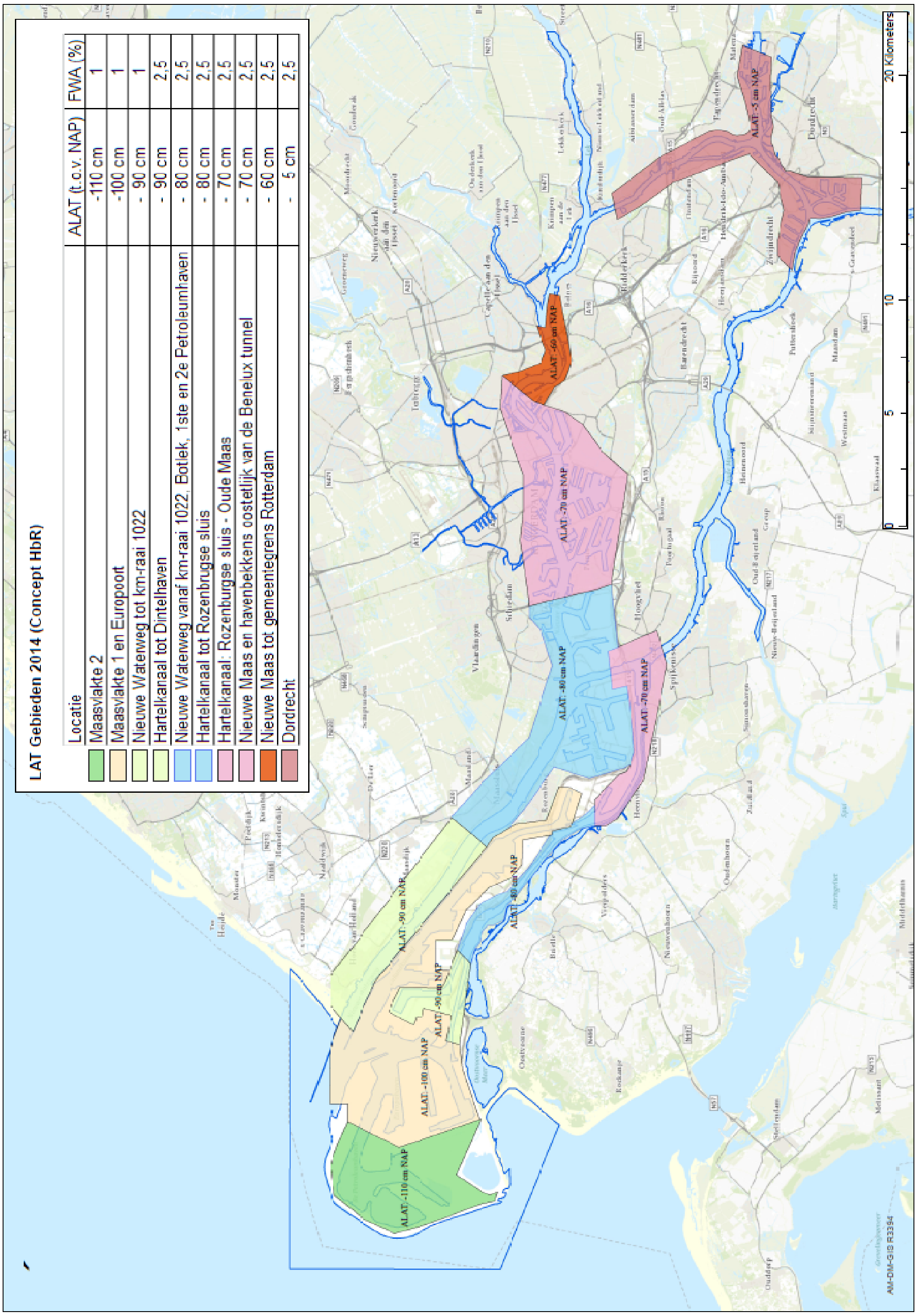


Standardised Depth Terminology (1.16)

Crown Copyright ©
Depth Diagram and associated Glossary extracted from the ADMIRALTY Mariner's Handbook, NP100.

Figure B.2: Standardised depth terminology by UK Hydrographic Office [2020]

B.2 ALAT and FWA



LAT Gebieden 2014 (Concept HbR)

	Locatie	ALAT (t.o.v. NAP)	FWA (%)
🟩	Maasvlakte 2	-110 cm	1
🟨	Maasvlakte 1 en Europoort	-100 cm	1
🟨	Nieuwe Waterweg tot km-raai 1022	- 90 cm	1
🟨	Hartelkanaal tot Dintelhaven	- 90 cm	2,5
🟦	Nieuwe Waterweg vanaf km-raai 1022, Botlek, 1ste en 2e Petroleumhaven	- 80 cm	2,5
🟦	Hartelkanaal tot Rozenburgse sluis	- 80 cm	2,5
🟪	Hartelkanaal: Rozenburgse sluis - Oude Maas	- 70 cm	2,5
🟪	Nieuwe Maas en havenbekkens oostelijk van de Benelux tunnel	- 70 cm	2,5
🟧	Nieuwe Maas tot gemeentegrens Rotterdam	- 60 cm	2,5
🟥	Dordrecht	- 5 cm	2,5

Figure B.3: ALAT and FWA in PoR area [Port of Rotterdam: DHMR, 2019]

The HME margin is 0.3 m for all subareas and is used for both sea and inland shipping [Port of Rotterdam: DHMR, 2019]. Furthermore, the ALAT values are derived from the 2006 LAT matrix of the hydriography department (military department that makes sea charts). A transition to the LAT matrix 2018 is currently ongoing. The *2e Maasvlakte* was not yet completed in 2006, perhaps some minor differences will arise.

B.3 $HW_{99\%}$ and ΔH

About Table B.2: for the Hoek van Holland and Krimpen a/d IJssel locations, the data is obtained by Rijkswaterstaat in the period of 1990 - 2011. The data for the other locations is obtained by the Port Authority in the period of 2004 - 2011. To explain Table B.1 with an example; for Hoek van Holland, 99% of the high waters are higher than NAP + 0.48 m.

HW	**99%**		**98%**		**95%**		**90%**	
	ALAT [cm]	NAP [cm]	ALAT [cm]	NAP [cm]	ALAT [cm]	NAP [cm]	ALAT [cm]	NAP [cm]
Hoek van Holland	148	48	156	56	167	67	178	78
Geulhaven (Botlek)	144	64	151	71	163	83	172	92
1e Eemhaven	141	71	221	77	159	89	169	99
Parkhaven	141	71	146	76	158	88	169	99
Krimpen a/d IJssel	?	62	?	70	?	81	?	89
Tennesseehaven	152	52	157	57	170	70	183	83
Europahaven	153	53	161	61	175	75	186	86
Hartelhaven	156	56	159	59	172	72	184	84
Suurhoffbrug (grens)	147	57	148	58	160	70	170	80
Hartelkanaal Q8	136	56	144	64	156	76	166	86
Harmsenbrug	143	63	147	67	158	78	168	88
Rozenburgse Sluis (Hartelzijde) (grens)	141	61	145	65	156	76	166	86
Hartelbrug	137	67	139	69	150	80	160	90
Scheurhaven	153	53	161	61	174	74	186	86
Rozenburgse Sluis (Calandzijde)	153	53	158	58	172	72	185	85

Table B.1: HW values [Port of Rotterdam: DHMR, 2019]

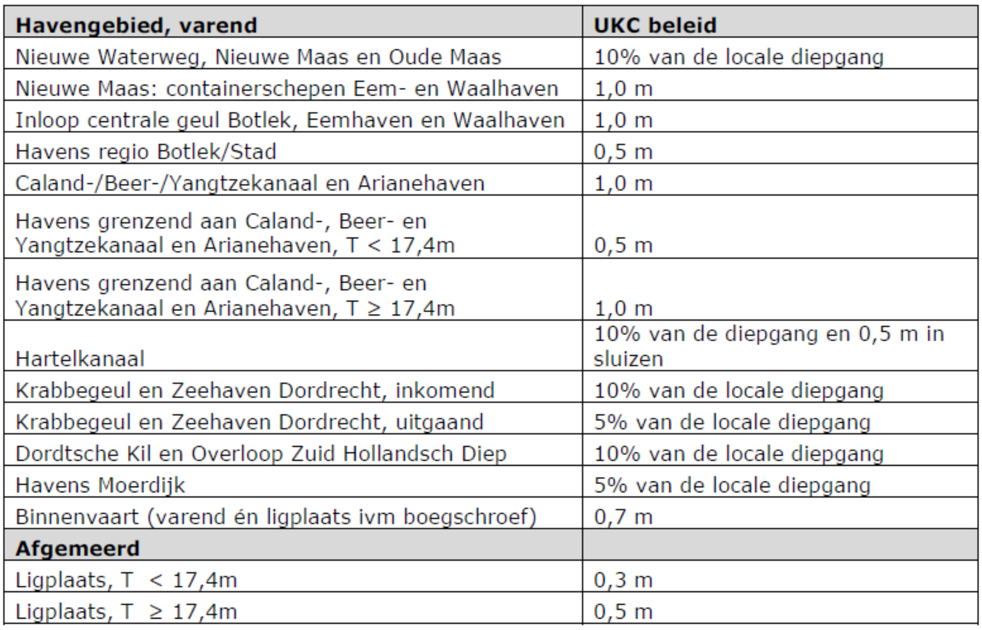
Berth/location	**Inbound passage LL at HW**		**Outbound unmoored at local HW**	
	Travel time [u] From HvH	**Tidal offset [cm]**	**Travel time [u] Till HvH**	**Tidal offset [cm] HvH**
Till entrance Botlek/3e Pet	1,0	10	Nvt	
2e werkhaven STR	1,4	15	1,3	37
Boeispan 66	2,0	30	1,8	52
Boeispan 62	2,1	32	1,9	57
In the back of 3e Pet	1,8	26	1,6	45
Till entrance 1e Pet	1,2	7	Nvt	
In the back of 1e Pet	1,7	20	1,5	45
Till entrance 2e Pet	1,3	15	Nvt	
In the back of 2e Pet	1,8	23	1,6	47
Till entrance Eemhaven	1,4	13	Nvt	
In the back of Eemhaven	1,9	25	1,7	57
Till entrance Waalhaven	1,5	15	nvt	
In the back of Waalhaven	2,0	27	1,8	59
Dordrecht	3,0		3,0	117
Moerdijk	3,7		3,7	127

Table B.2: ΔH values used for determining HW99% [Port of Rotterdam: DHMR, 2019]

- LL = *Lage Licht* (Lower Leading Light), which is very close to Hoek van Holland. It is a guidance point for vessels entering the port.
- First line ashore = inbound.
- Last line off = outbound

B.4 UKC policy

Static UKC policy is inside the PoR, a different DUKC-policy applies outside the port (in the approach channel).

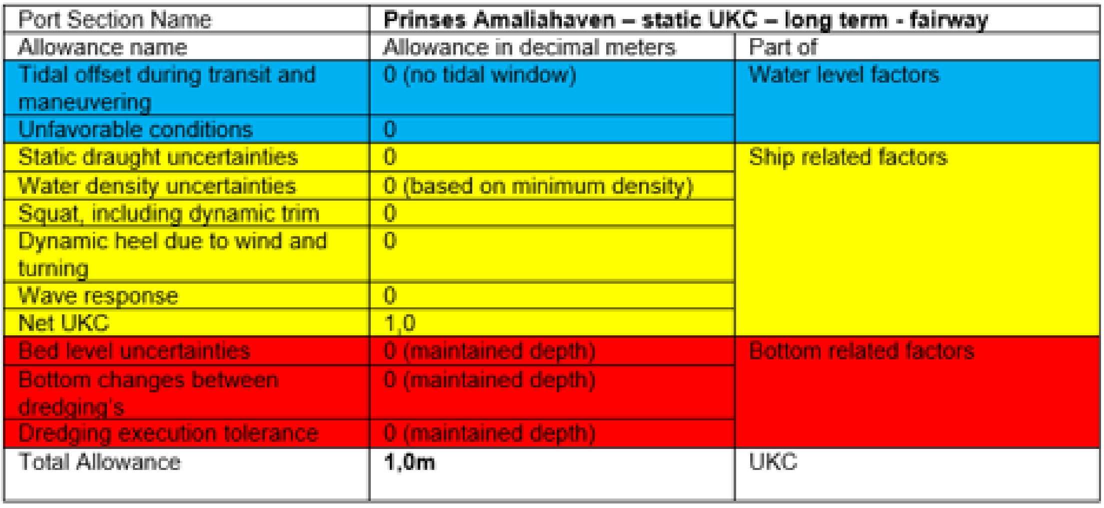


Havengebied, varend	**UKC beleid**
Nieuwe Waterweg, Nieuwe Maas en Oude Maas	10% van de locale diepgang
Nieuwe Maas: containerschepen Eem- en Waalhaven	1,0 m
Inloop centrale geul Botlek, Eemhaven en Waalhaven	1,0 m
Havens regio Botlek/Stad	0,5 m
Caland-/Beer-/Yangtzekanaal en Arianehaven	1,0 m
Havens grenzend aan Caland-, Beer- en Yangtzekanaal en Arianehaven, T < 17,4m	0,5 m
Havens grenzend aan Caland-, Beer- en Yangtzekanaal en Arianehaven, T ≥ 17,4m	1,0 m
Hartelkanaal	10% van de diepgang en 0,5 m in sluizen
Krabbegeul en Zeehaven Dordrecht, inkomend	10% van de locale diepgang
Krabbegeul en Zeehaven Dordrecht, uitgaand	5% van de locale diepgang
Dordtsche Kil en Overloop Zuid Hollandsch Diep	10% van de locale diepgang
Havens Moerdijk	5% van de locale diepgang
Binnenvaart (varend én ligplaats ivm boegschroef)	0,7 m
Afgemeerd	
Ligplaats, T < 17,4m	0,3 m
Ligplaats, T ≥ 17,4m	0,5 m

Figure B.4: UKC policy as imposed by PoR (sea shipping): minimum UKC for sailing vessels [Port of Rotterdam: DHMR, 2019]

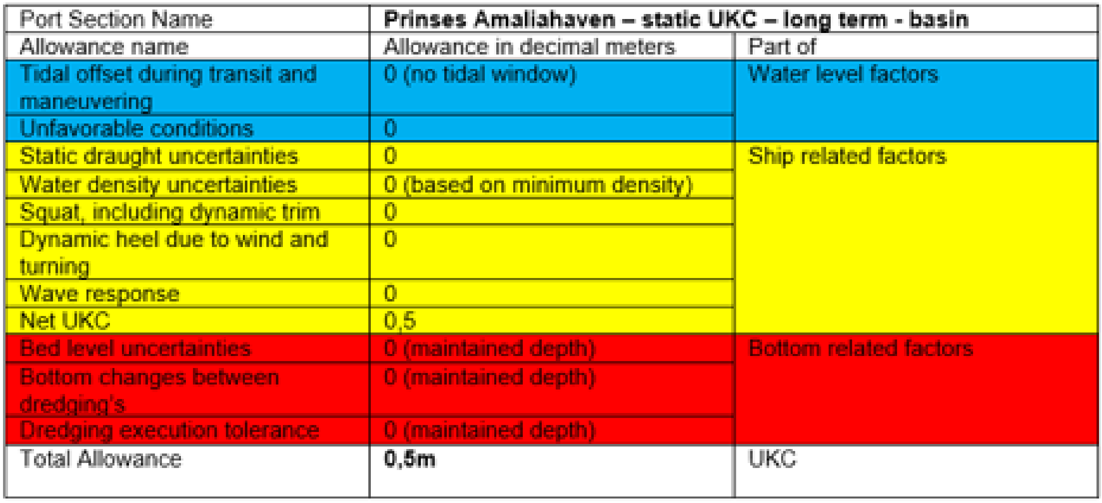
An example of how the UKC was build-up, using PIANC guidelines, by the PoR for a container vessel to the *Prinses Amaliahaven* is provided in Figure B.5. A distinction is made between short term (< 36hours) and long term (>36 hours) vessel arrivals. Figure B.5 presents the port sections on this trajectory.

Figure B.5: Port sections on *Prinses Amaliahaven* trajectory



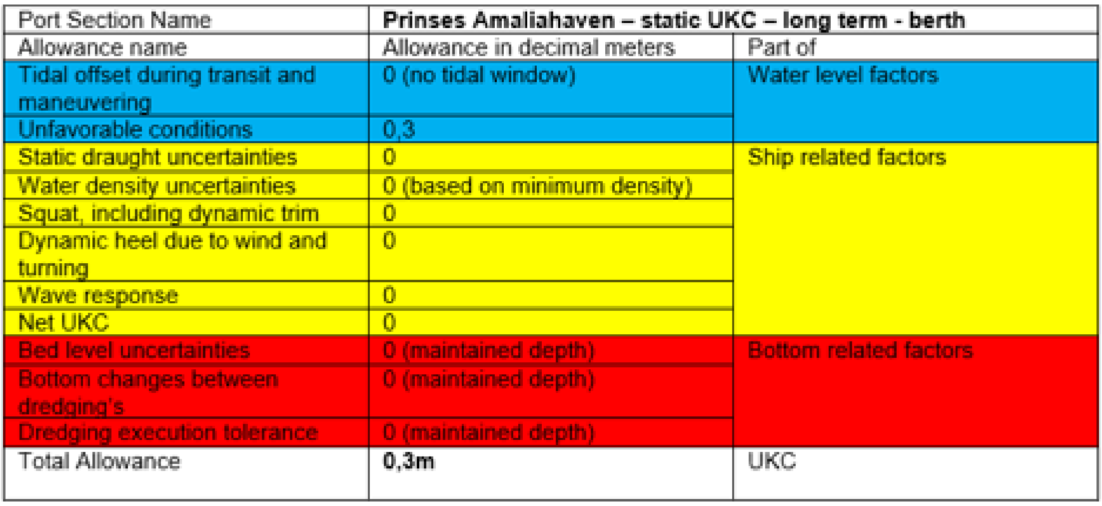
Port Section Name	**Prinses Amaliahaven – static UKC – long term - fairway**	
Allowance name	Allowance in decimal meters	Part of
Tidal offset during transit and maneuvering	0 (no tidal window)	Water level factors
Unfavorable conditions	0	
Static draught uncertainties	0	Ship related factors
Water density uncertainties	0 (based on minimum density)	
Squat, including dynamic trim	0	
Dynamic heel due to wind and turning	0	
Wave response	0	
Net UKC	1,0	
Bed level uncertainties	0 (maintained depth)	Bottom related factors
Bottom changes between dredging's	0 (maintained depth)	
Dredging execution tolerance	0 (maintained depth)	
Total Allowance	**1,0m**	UKC

(a) Static UKC - long term - fairway



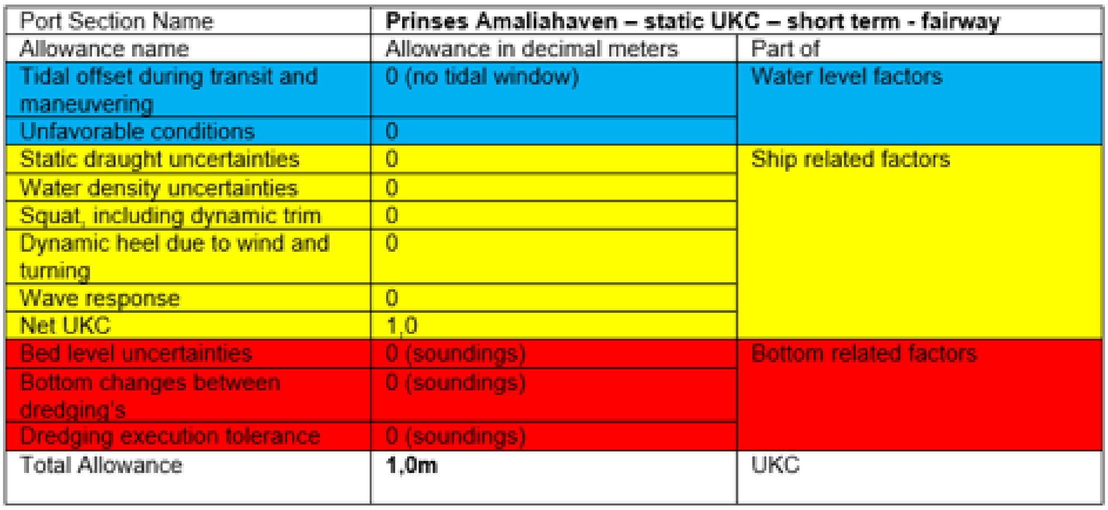
Port Section Name	**Prinses Amaliahaven – static UKC – long term - basin**	
Allowance name	Allowance in decimal meters	Part of
Tidal offset during transit and maneuvering	0 (no tidal window)	Water level factors
Unfavorable conditions	0	
Static draught uncertainties	0	Ship related factors
Water density uncertainties	0 (based on minimum density)	
Squat, including dynamic trim	0	
Dynamic heel due to wind and turning	0	
Wave response	0	
Net UKC	0,5	
Bed level uncertainties	0 (maintained depth)	Bottom related factors
Bottom changes between dredging's	0 (maintained depth)	
Dredging execution tolerance	0 (maintained depth)	
Total Allowance	**0,5m**	UKC

(b) Static UKC - long term - basin



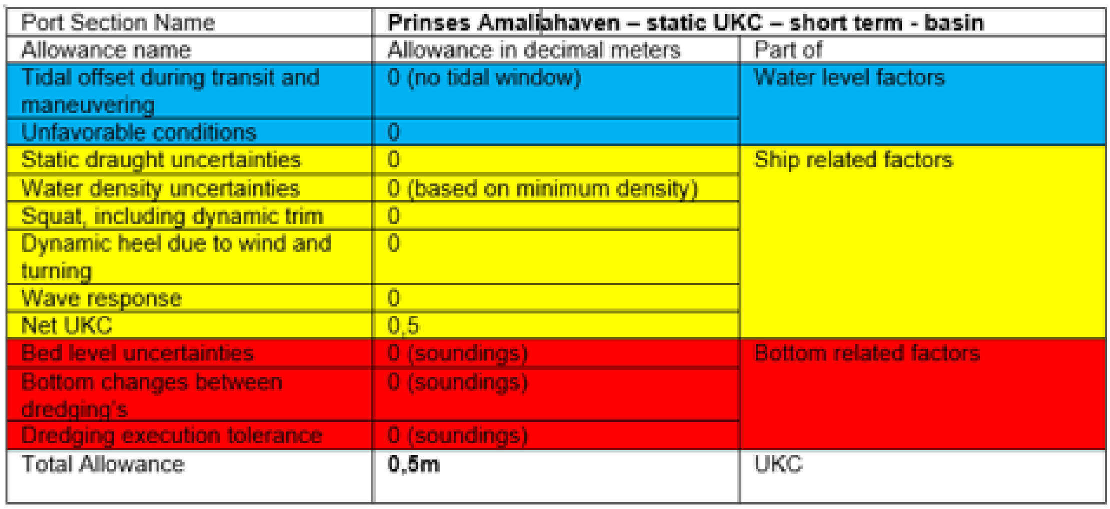
Port Section Name	**Prinses Amaliahaven – static UKC – long term - berth**	
Allowance name	Allowance in decimal meters	Part of
Tidal offset during transit and maneuvering	0 (no tidal window)	Water level factors
Unfavorable conditions	0,3	
Static draught uncertainties	0	Ship related factors
Water density uncertainties	0 (based on minimum density)	
Squat, including dynamic trim	0	
Dynamic heel due to wind and turning	0	
Wave response	0	
Net UKC	0	
Bed level uncertainties	0 (maintained depth)	Bottom related factors
Bottom changes between dredging's	0 (maintained depth)	
Dredging execution tolerance	0 (maintained depth)	
Total Allowance	**0,3m**	UKC

(c) Static UKC - long term - berth



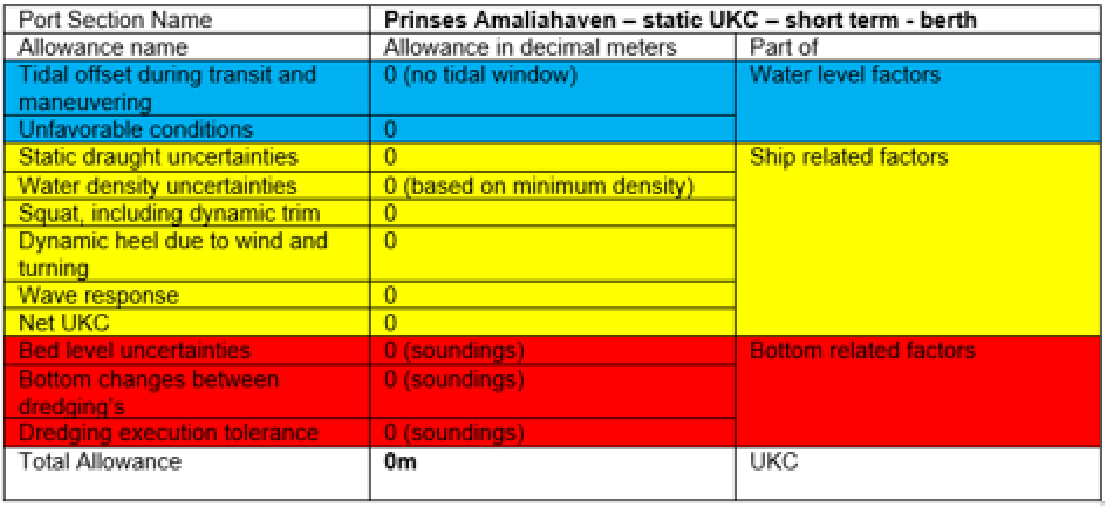
Port Section Name	**Prinses Amaliahaven – static UKC – short term - fairway**	
Allowance name	Allowance in decimal meters	Part of
Tidal offset during transit and maneuvering	0 (no tidal window)	Water level factors
Unfavorable conditions	0	
Static draught uncertainties	0	Ship related factors
Water density uncertainties	0	
Squat, including dynamic trim	0	
Dynamic heel due to wind and turning	0	
Wave response	0	
Net UKC	1,0	
Bed level uncertainties	0 (soundings)	Bottom related factors
Bottom changes between dredging's	0 (soundings)	
Dredging execution tolerance	0 (soundings)	
Total Allowance	**1,0m**	UKC

(d) Static UKC - short term - fairway



Port Section Name	**Prinses Amaliahaven – static UKC – short term - basin**	
Allowance name	Allowance in decimal meters	Part of
Tidal offset during transit and maneuvering	0 (no tidal window)	Water level factors
Unfavorable conditions	0	
Static draught uncertainties	0	Ship related factors
Water density uncertainties	0 (based on minimum density)	
Squat, including dynamic trim	0	
Dynamic heel due to wind and turning	0	
Wave response	0	
Net UKC	0,5	
Bed level uncertainties	0 (soundings)	Bottom related factors
Bottom changes between dredging's	0 (soundings)	
Dredging execution tolerance	0 (soundings)	
Total Allowance	**0,5m**	UKC

(e) Static UKC - short term - basin



Port Section Name	**Prinses Amaliahaven – static UKC – short term - berth**	
Allowance name	Allowance in decimal meters	Part of
Tidal offset during transit and maneuvering	0 (no tidal window)	Water level factors
Unfavorable conditions	0	
Static draught uncertainties	0	Ship related factors
Water density uncertainties	0 (based on minimum density)	
Squat, including dynamic trim	0	
Dynamic heel due to wind and turning	0	
Wave response	0	
Net UKC	0	
Bed level uncertainties	0 (soundings)	Bottom related factors
Bottom changes between dredging's	0 (soundings)	
Dredging execution tolerance	0 (soundings)	
Total Allowance	**0m**	UKC

(f) Static UKC - short term - berth

Figure B.5: Example of UKC build-up by PoR on *Prinses Amaliahaven* trajectory

C Vertex-names in network

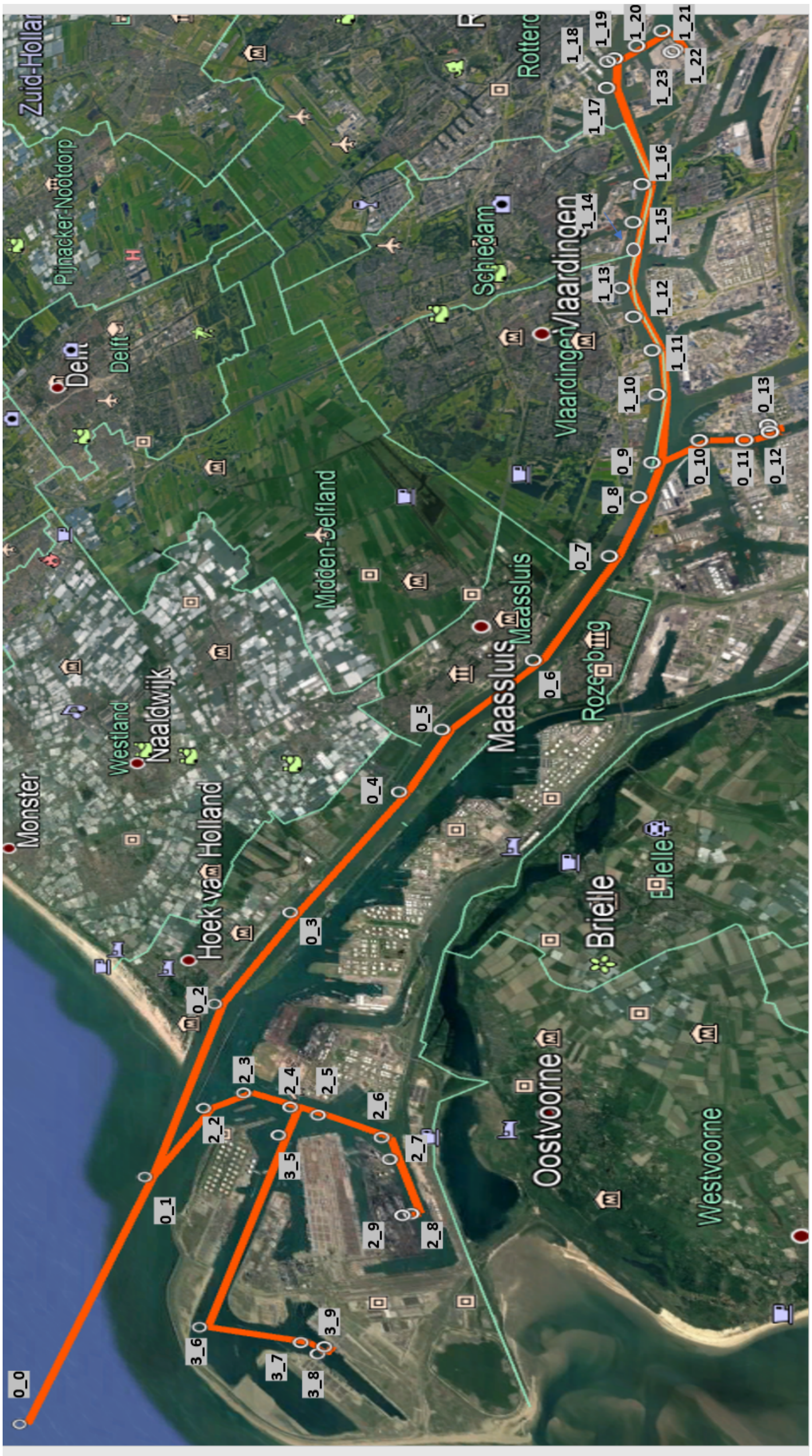
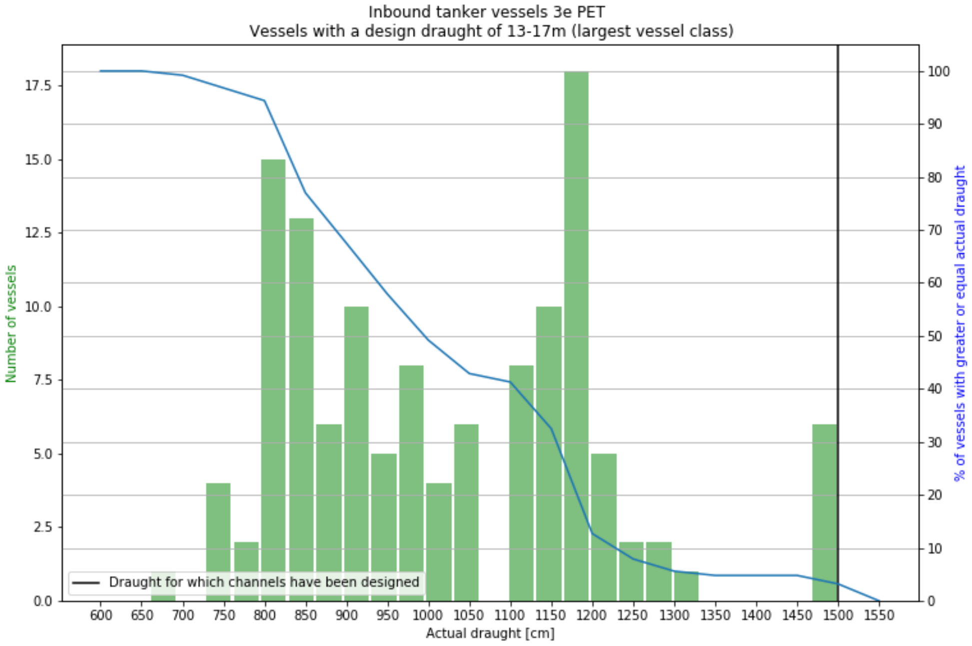
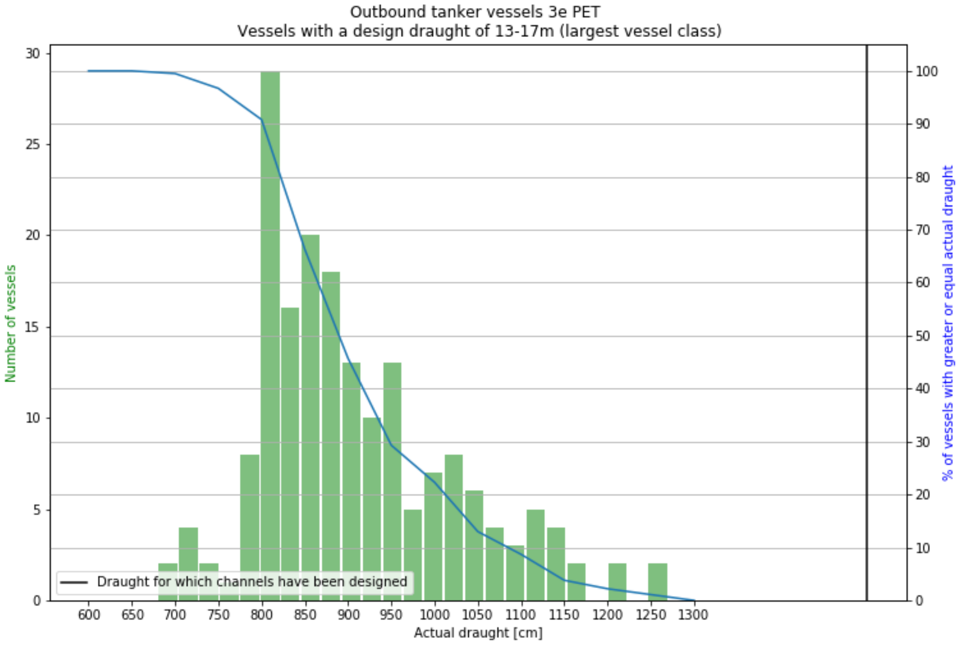


Figure C.1: Vertices' names in graph (as used in computer model)

D Supplementary traffic data analysis

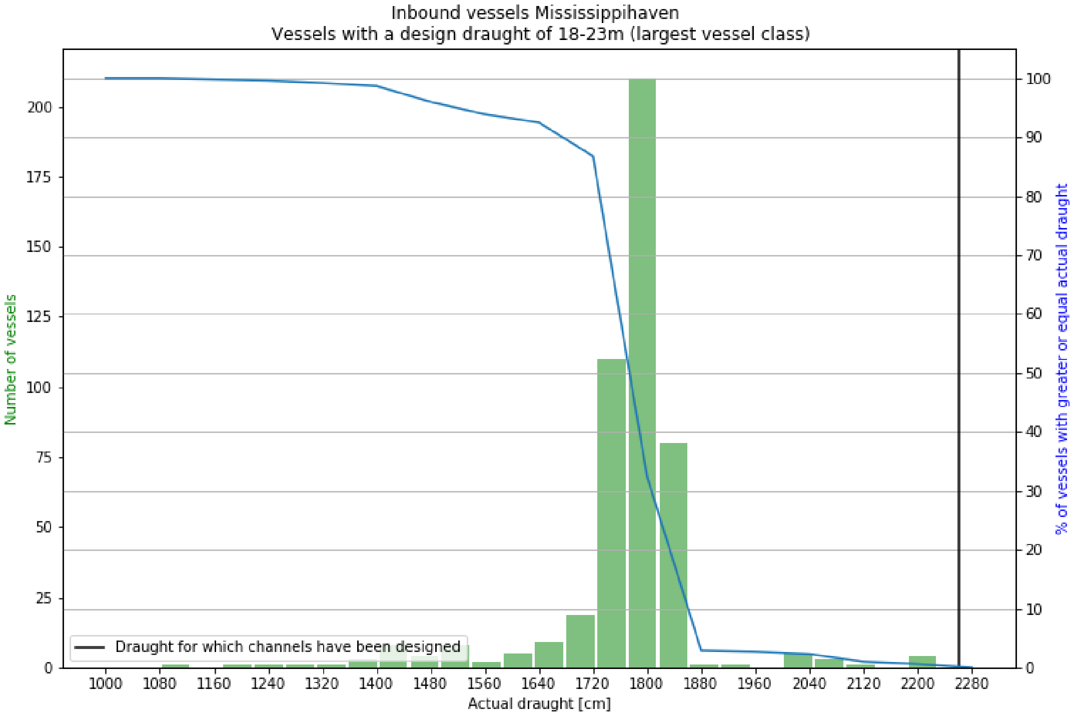


(a) Inbound vessels Koole terminal

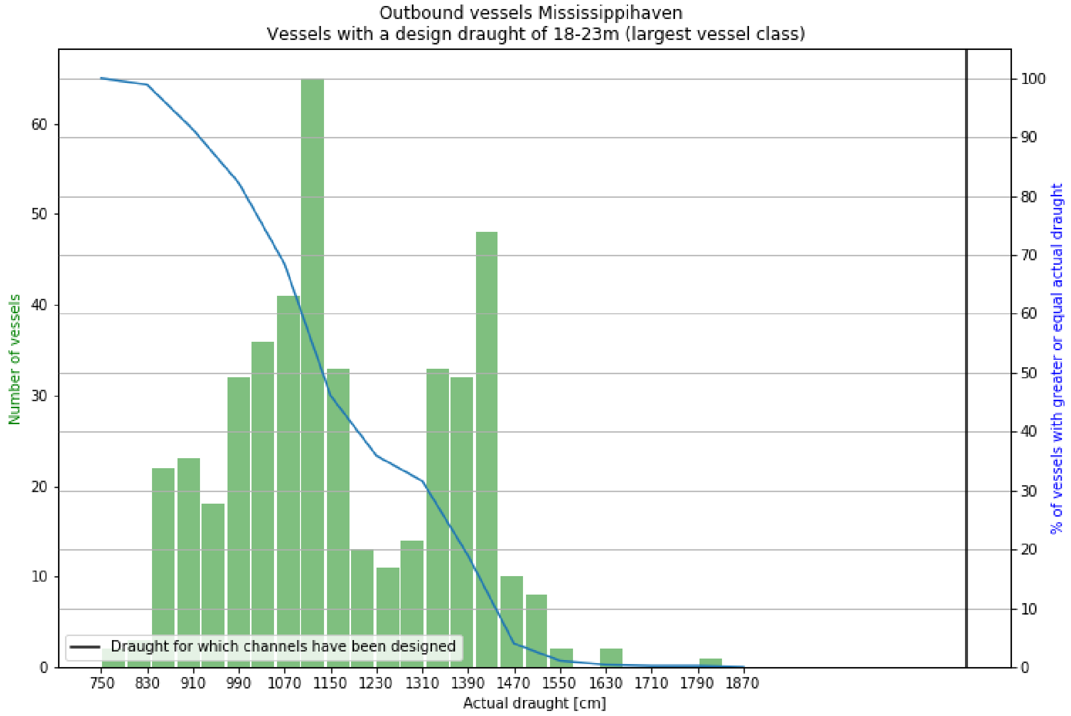


(b) Outbound vessels Koole terminal

Figure D.1: Actual vessel draught distribution of largest in- and outbound vessels 3e PET (data from HaMIS: January 2015 - February 2020)



(a) Inbound vessels EMO terminal



(b) Outbound vessels EMO terminal

Figure D.2: Actual vessel draught distribution of largest in- and outbound vessels Mississippihaven (data from HaMIS: January 2015 - February 2020)

E Model input

E.1 Local conditions (data)

Measurements are taken every 10 minutes, so the data goes in this step size. Predicted height of tides are used for the local water levels. This is built by the PoR from a combination of measured water levels and astronomical predictions. Predicted water levels were used because numbers were often missing from the measured water level data set. The difference between measured and predicted water levels is very small. The same holds for tidal stream rates and directions. Moreover, the relevant depth over which a tidal stream rate has been measured can differ per port basin. The same types of tidal stream rates and directions as used by the Harbour Coordination Center have been applied.

The locations of the local conditions (data) were presented in Figure 4.6.

🟦 6PETH / PH10
Predicted height of tide 10 minutes
🟨 CKNIJLH / PH10
Predicted height of tide 10 minutes
🟪 MISSH / PH10
Predicted height of tide 10 minutes
🟩 AMALH / PH10
Predicted height of tide 10 minutes
🟧 PADD / PH10
Predicted height of tide 10 minutes
⬜ HOEK / PH10
Predicted height of tide 10 minutes
🟦 MAESLKZZ / PH10
Predicted height of tide 10 minutes
🟨 MAAS / PH10
Predicted height of tide 10 minutes
🟪 RP10 / PH10
Predicted height of tide 10 minutes
🟩 VLAA / PH10
Predicted height of tide 10 minutes
🟧 WILTHM / PH10
Predicted height of tide 10 minutes
⬜ WAALHNM / PH10
Predicted height of tide 10 minutes
🟦 SCHEUK / PH10
Predicted height of tide 10 minutes

(a) Local water levels

🟦 BEERGHK / PTSR10S5
Predicted tidal stream rate 10 minutes from surface to 5 meters
🟨 BEERGHK / PTSD10S5
Predicted tidal stream direction 10 minutes from surface to 5 meters
🟪 SCHEUK / PTSR10S15
Predicted tidal stream rate 10 minutes from surface to 15 meters
🟩 SCHEUK / PTSD10S15
Predicted tidal stream direction 10 minutes from surface to 15 meters
🟧 WAALHNM / PTSRDA10
Predicted tidal stream rate 10 minutes depth averaged
⬜ WAALHNM / PTSDDA10
Predicted tidal stream direction 10 minutes depth averaged

(b) Local currents

Figure E.1: Names of local conditions data in model

E.2 Vessel speeds based on AIS lines

Figures of AIS lines in the PoR are presented in Section E.2.1. Vessel speeds are determined with the formula below. The results are presented in Section E.2.2

$$v = \frac{s_{from,to}}{t_{from,to}} \tag{E.1}$$

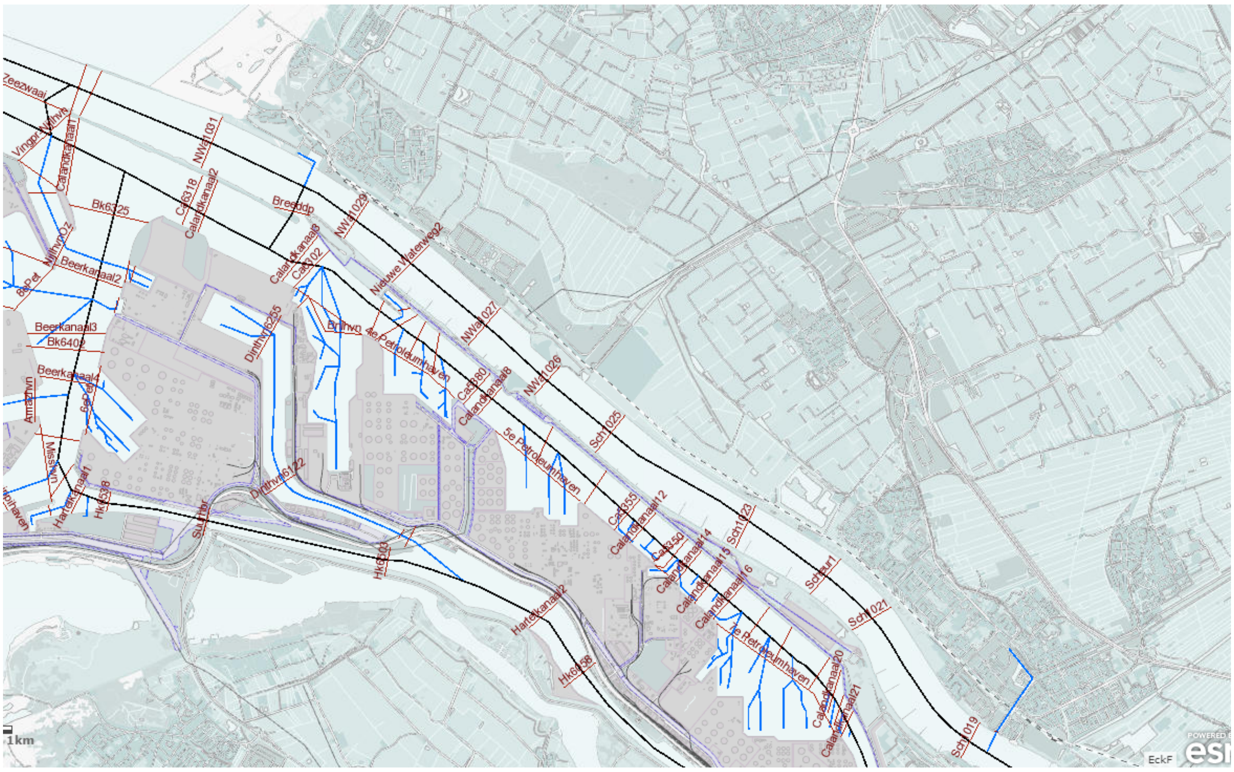
Where:

v = vessel speed [km/hr]
$s_{from,to}$ = distance between 'from AIS line' and 'to AIS line' [km]
$t_{from,to}$ = arrival time at 'from AIS line' - arrival time at 'to AIS line'[hours]

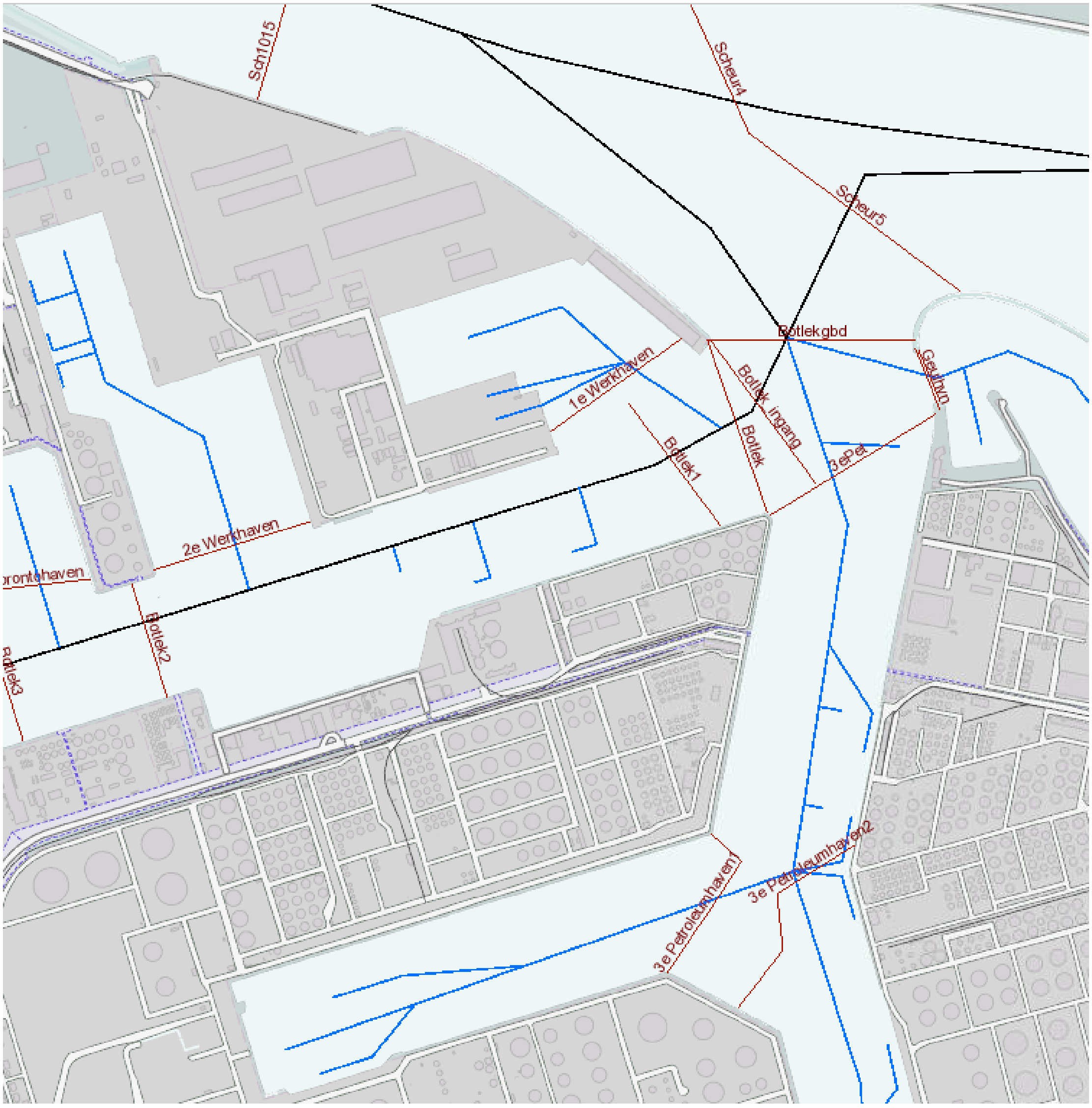
There are often no counting lines at the berth site, for this first or last part of the route a speed of 3 km/h has been assumed (based on HCC questioning). Vertices and counting lines do not always coincide exactly. Therefore, the speeds between two counting lines in which an edge finds itself have been used.

The program that turns this AIS data into passing moments for the PoR is called the 'passage-monitor'. The largest vessel classes handled at the associated terminals since 2019 are analysed.

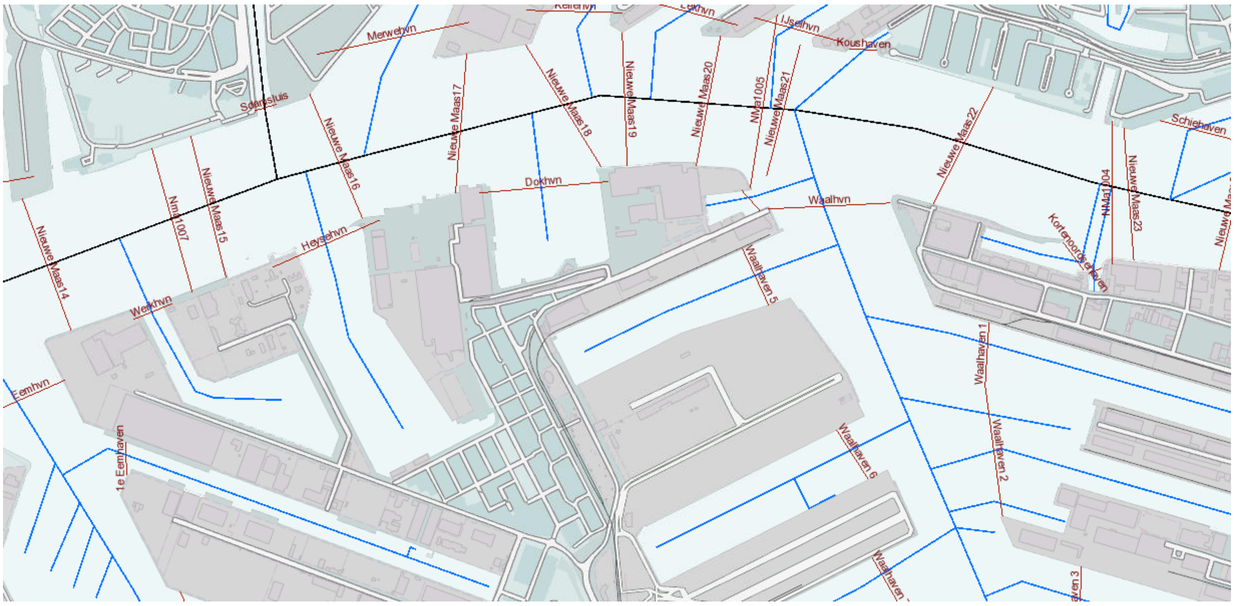
E.2.1 Detailed figures of AIS lines



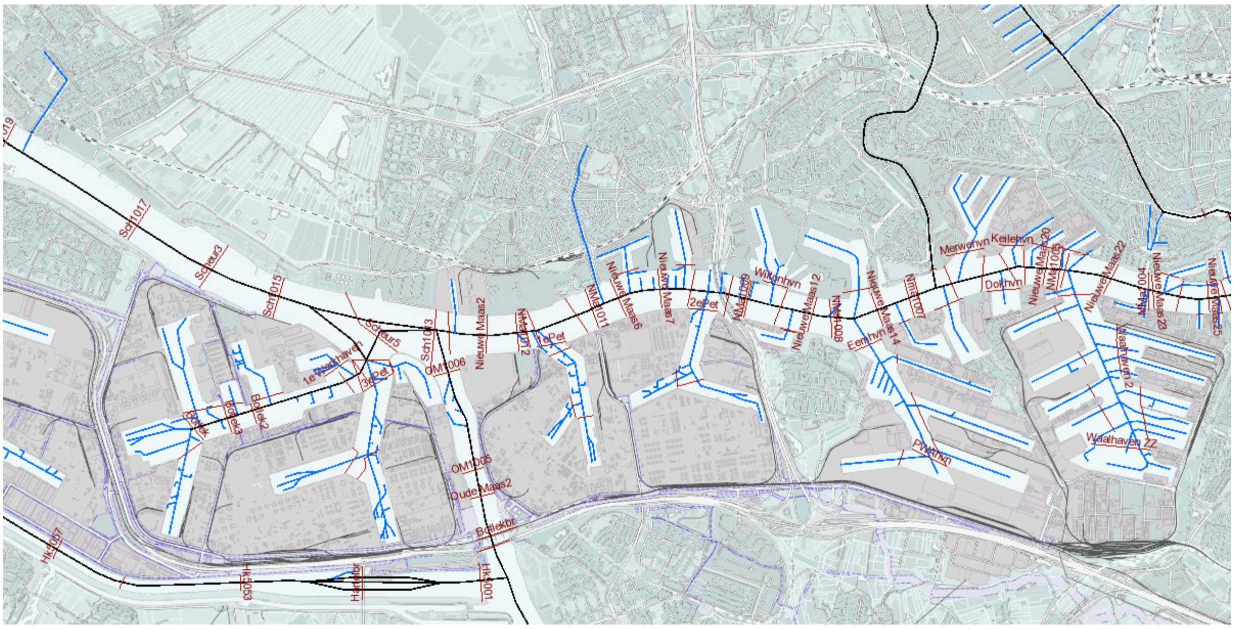
(a) AIS lines in detail Hoek van Holland - Maassluis



(b) AIS lines in detail 3e Petroleumhaven



(c) AIS lines in detail Waalhaven



(d) AIS lines in detail Maassluis-city

(e) AIS lines in detail Maasvlakte 2

Figure E.-2: Detailed figures of AIS lines in PoR

E.2.2 Results vessel speeds

Table E.1 presents the number of vessel journeys on which the results in Table E.2 till Table Fig E.9 are based.

Port basin	Number of vessels on which inbound results are based	Number of vessels on which outbound results are based
3e Petroleumhaven	3	3
Waalhaven	4	2
Mississippihaven	4	4
Prinses Amaliahaven	4	4

Table E.1: Number of analysed vessel journeys

From AIS line	**To AIS line**	**Corresponds approx. to edges**	**Vmin**	**Vaverage**	**Vmax**
binnencontour PM	NWA 1035	0_0 through 0_1	13	16	18
NWA 1035	Scheur 1	0_1 through 0_5	14	16	17
Scheur 1	Botlekgebied	0_5 through 0_10	9	9	10
Botlekgebied	3ePet	0_10 through 0_11	4	4	4
3ePet	3e Petroleumhaven2	0_11 through 0_12	3	3	4

Table E.2: Speeds along trajectory of largest-draughted inbound vessels 3e Petroleumhaven

From AIS line	**To AIS line**	**Corresponds approx. to edges**	**Vmin**	**Vaverage**	**Vmax**
3ePet	Botlekgebied	0_10 through 0_11	5	7	8
Botlekgebied	Scheur 1	0_5 through 0_10	14	16	17
Scheur 1	NWA 1035	0_1 through 0_5	19	21	23
NWA 1035	binnencontour PM	0_0 through 0_1	24	26	28

Table E.3: Speeds along trajectory of largest-draughted outbound vessels 3e Petroleumhaven

From AIS line	**To AIS line**	**Corresponds approx. to edges**	**Vmin**	**Vaverage**	**Vmax**
binnencontour PM	NWA 1035	0_0 through 0_1	17	21	24
NWA 1035	Sch 1021	0_1 through 0_5	13	16	19
Sch 1021	NMa 1005	0_5 through 1_18	12	13	15
NMa 1005	Waalhaven	1_18 through 1_20	11	14	17

Table E.4: Speeds along trajectory of largest-draughted inbound vessels Waalhaven

From AIS line	**To AIS line**	**Corresponds approx. to edges**	**Vmin**	**Vaverage**	**Vmax**
Waalhaven	NMa 1005	1_20 through 1_18	17	17	17
NMa 1005	Sch 1021	1_18 through 0_5	12	13	13
Sch 1021	NWA 1035	0_5 through 0_1	14	18	21
NWA 1035	binnencontour PM	0_1 through 0_0	21	24	28

Table E.5: Speeds along trajectory of largest-draughted outbound vessels Waalhaven

From AIS line	**To AIS line**	**Corresponds approx. to edges**	**Vmin**	**Vaverage**	**Vmax**
binnencontourPM	Bk 6325	0_0 through 2_3	13	14	16
Bk 6325	Bk 6402	2_3 through 2_5	8	9	10
Bk 6402	Mississippihaven	2_5 through 2_7	6	11	13

Table E.6: Speeds along trajectory of largest-draughted inbound vessels Mississippihaven

From AIS line	**To AIS line**	**Corresponds approx. to edges**	**Vmin**	**Vaverage**	**Vmax**
Mississippihaven	Bk 6402	2_7 through 2_5	9	10	13
Bk 6402	Bk 6325	2_5 through 2_3	7	10	12
Bk 6325	binnencontourPM	2_3 through 0_0	16	19	20

Table E.7: Speeds along trajectory of largest-draughted outbound vessels Mississippihaven

From AIS line	**To AIS line**	**Corresponds approx. to edges**	**Vmin**	**Vaverage**	**Vmax**
binnencontourPM	Calandkanaal1	0_0 -2_2	14	17	21
Calandkanaal1	Beerkanaal2	2_2 - 2_4	11	13	15
Beerkanaal2	Yangtzekanaal 9825	2_4 -3_6	8	9	10
Yangtzekanaal 9825	Prinses Amaliahaven	3_6 - 3_7	6	7	8

Table E.8: Speeds along trajectory of largest-draughted inbound vessels Prinses Amaliahaven

From AIS line	**To AIS line**	**Corresponds approx. to edges**	**Vmin**	**Vaverage**	**Vmax**
Prinses Amaliahaven	Yangtzekanaal 9825	3_7 - 3_6	4	5	6
Yangtzekanaal 9825	Beerkanaal2	3_6 - 2_4	5	8	9
Beerkanaal2	Calandkanaal1	2_4 - 2_2	12	13	15
Calandkanaal1	binnencontourPM	2_2 - 0_0	22	22	23

Table E.9: Speeds along trajectory of largest-draughted outbound vessels Prinses Amaliahaven

E.3 Channel dimensions

The length, width and current MBL of edges and berths are presented in the Table E.10.

Edge	Length [m]	Width [m]	Current MBL [cm wrt NAP]
vertex-0_0, vertex-0_1	8264	550	-2430
vertex-0_1, vertex-0_2	5062	270	-1620
vertex-0_2, vertex-0_3	3044	270	-1620
vertex-0_3, vertex-0_4	3856	270	-1620
vertex-0_4, vertex-0_5	1720	270	-1620
vertex-0_5, vertex-0_6	2370	200	-1640
vertex-0_6, vertex-0_7	2640	200	-1640
vertex-0_7, vertex-0_8	1344	200	-1640
vertex-0_8, vertex-0_9	760	200	-1640
vertex-0_9, vertex-0_10	895	200	-1590
vertex-0_10, vertex-0_11	754	150	-1590
vertex-0_11, vertex-0_12	431	150	-1590
vertex-0_12, vertex-0_13	145	150	-1590
vertex-0_13 (berth)	330	70	-1700
vertex-0_1, vertex-2_2	2521	415	-2380
vertex-2_2, vertex-2_3	1104	460	-2380
vertex-2_3, vertex-2_4	1101	290	-2365
vertex-2_4, vertex-2_5	636	230	-2365
vertex-2_5, vertex-2_6	1419	230	-2365
vertex-2_6, vertex-2_7	518	230	-2365
vertex-2_7, vertex-2_8	1289	220	-2400
vertex-2_8, vertex-2_9	197	220	-2400
vertex-2_9 (berth)	500	60	-2300
vertex-1_14, vertex-1_15	702	170	-1450
vertex-1_15, vertex-1_16	807	170	-1450
vertex-1_16, vertex-1_17	2361	170	-1450
vertex-1_17, vertex-1_18	578	170	-1450
vertex-1_18, vertex-1_19	128	320	-1450
vertex-1_19, vertex-1_20	422	320	-1450
vertex-1_20, vertex-1_21	483	200	-1425
vertex-1_21, vertex-1_22	526	200	-1425
vertex-1_22, vertex-1_23	62	200	-1425
vertex-1_23 (berth)	750	70	-1415
vertex-2_4, vertex-3_5	788	350	-1965
vertex-3_5, vertex-3_6	5590	400	-1965
vertex-3_6, vertex-3_7	2401	400	-1965
vertex-3_7, vertex-3_8	418	450	-1965
vertex-3_8, vertex-3_9	264	450	-1965
vertex-3_9 (berth)	800	100	-1965

Table E.10: Dimensions of channels (edges)

E.4 Duration at berth analysis

Actual draught (arrival) [cm]	**Duration at berth** [seconds]	**Duration at berth** [days]
2230	363300	4,2
2210	517080	6,0
2210	547860	6,3
2190	624060	7,2
2130	443100	5,1

Table E.11: Duration at berth - Mississippihaven EMO terminal - channel design draught

Actual draught (arrival) [cm]	**Duration at berth** [seconds]	**Duration at berth** [days]
1862	348000	4,0
1850	316020	3,7
1850	259980	3,0
1850	209160	2,4
1849	406860	4,7

Table E.12: Duration at berth - Mississippihaven EMO terminal - alternative actual draught

Actual draught (arrival) [cm]	**Duration at berth** [seconds]	**Duration at berth** [days]
1500	320640	3,7
1500	338040	3,9
1500	417480	4,8
1495	260640	3,0
1490	419100	4,9

Table E.13: Duration at berth - 3e Petroliumhaven Koole terminal - channel design draught

Actual draught (arrival) [cm]	**Duration at berth** [seconds]	**Duration at berth** [days]
1650	152640	1,8
1650	134760	1,6
1650	153540	1,8
1650	147360	1,7
1650	208080	2,4

Table E.14: Duration at berth - Prinses Amaliahaven APM terminal - alternative actual draught

Actual draught (arrival) [cm]	**Duration at berth** [seconds]	**Duration at berth** [days]
1350	120600	1,4
1350	95040	1,1
1350	93720	1,1
1350	56640	0,7
1340	94080	1,1

Table E.15: Duration at berth - Waalhaven Uniport terminal - channel design draught

Actual draught (arrival) [cm]	**Duration at berth** [seconds]	**Duration at berth** [days]
1300	177780	2,1
1300	152580	1,8
1300	145200	1,7
1300	150060	1,7
1300	135960	1,6

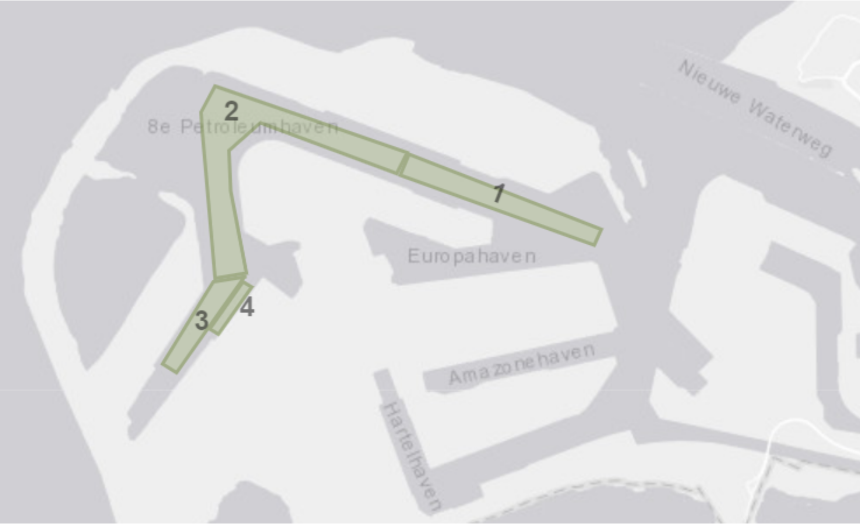
Table E.16: Duration at berth - Waalhaven Uniport terminal - alternative actual draught

F Vertical design trajectory *Prinses Amaliahaven* using PoR's own design standards

F.1 Sections

In Figure F.1 the current and proposed maintained bed level sections can be compared. Between section 1 and 2 a new ALAT-zone begins. Between section 2 (fairway), 3 (basin) and 4 (berth) a different UKC policy is applied.

(a) Current maintained bed level section



(b) Proposed maintained bed level sections

Figure F.1: Current and proposed maintained bed level sections *Prinses Amaliahaven* trajectory

F.2 Result current situation

New maintained bed levels are calculated by dividing the sections as presented in Figure F.1 and using Equation 2.2 (the formula the PoR uses to design on low tide). The results are presented in Table F.1.

	Section 1	**Section 2**	**Section 3**	**Section 4 (berth)**
UKC [m]	-1	-1	-0,5	-0,3
FWA [%]	1%	1%	1%	1%
Tmax [m]	-17	-17	-17	-17
HME [m]	-0,3	-0,3	-0,3	-0,3
ALAT cm wrt NAP	-1	-1,1	-1,1	-1,1
Calculated MBL [m wrt NAP]	-19,47	-19,57	-19,07	-18,87
Current MBL [m wrt NAP]	-19,65	-19,65	-19,65	-19,65
Conservativeness [m]	0,18	0,08	0,58	0,78

Table F.1: Vertical design results *Prinses Amaliahaven* trajectory with PoR's own standards

G Overview of accessibility percentages of cases

The locations of vertices in the port-network were presented in Appendix C.

Edge	Current accessibility [%]
vertex-0_1, vertex-0_2	98.20
vertex-0_2, vertex-0_3	98.44
vertex-0_3, vertex-0_4	98.44
vertex-0_4, vertex-0_5	98.44
vertex-0_5, vertex-0_6	97.96
vertex-0_6, vertex-0_7	97.13
vertex-0_7, vertex-0_8	94.85
vertex-0_8, vertex-0_9	94.85
vertex-0_9, vertex-0_10	94.85
vertex-0_10, vertex-0_11	99.04
vertex-0_11, vertex-0_12	99.04
vertex-0_12, vertex-0_13	99.04
vertex-0_13 (berth)	97.37
vertex-2_2, vertex-2_3	98.91
vertex-2_3, vertex-2_4	97.61
vertex-2_4, vertex-2_5	97.61
vertex-2_5, vertex-2_6	97.61
vertex-2_6, vertex-2_7	97.61
vertex-2_7, vertex-2_8	99.57
vertex-2_8, vertex-2_9	99.57
vertex-2_9 (berth)	0.22
vertex-1_14, vertex-1_15	97.85
vertex-1_15, vertex-1_16	97.85
vertex-1_16, vertex-1_17	97.73
vertex-1_17, vertex-1_18	97.02
vertex-1_18, vertex-1_19	99.88
vertex-1_19, vertex-1_20	99.88
vertex-1_20, vertex-1_21	100
vertex-1_21, vertex-1_22	100
vertex-1_22, vertex-1_23	100
vertex-1_23 (berth)	6.09
vertex-2_4, vertex-3_5	99.95
vertex-3_5, vertex-3_6	99.94
vertex-3_6, vertex-3_7	99.94
vertex-3_7, vertex-3_8	100
vertex-3_8, vertex-3_9	100
vertex-3_9 (berth)	100

Table G.1: Current accessibility percentages on trajectories (excluding approach channel)

H Code archive

The MBL model is available at the GitHub of the TU Delft Hydraulic Engineering department. A link can be found in Figure H.1. Code to analyse traffic data can be found in this same repository.

Figure H.1: Link to the MBL model on the TU Delft Github: *https://github.com/TUDelft-CITG/MBL-model*