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OPTIMIZING BED LEVELS IN PORTS BASED ON PORT ACCESSIBILITY

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Ports strive to maximize their revenues through being sufficiently nautically accessible for sea-going vessels while minimizing dredging efforts, among many other objectives. These two objectives form an interesting trade-off as they are both dependent on the chosen maintained bed level. Due to system complexities, the design of maintained bed levels is typically optimized using individual design vessels, thereby neglecting the potential interactions between the in- and outgoing nautical traffic. These interactions may in fact be important. To investigate the effect of these interactions on port accessibility, a novel nautical traffic simulator has been built within an open-source discrete-event model. Application to a simple case study of a liquid bulk terminal in the Port of Rotterdam, shows that the interactions between the nautical traffic dynamics and the bed levels can lead to cascading effects that indeed reduce the accessibility and performance of a port. Further ongoing research with the nautical traffic model is expected to result in more accurate assessments of appropriate bed levels, compared to the current approaches.

Keywords: maintained bed level; under keel clearance; tidal window; port accessibility; nautical traffic model; discrete-event simulation model

INTRODUCTION

Over 80% of global cargo is transported over water through ports (UNCTAD 2021). In order to be viable and competitive, ports need to be accessible for various stakeholders: one of them is accessibility from a nautical-logistical perspective. A nautically accessible port ensures the safe and efficient transit of sea-going vessels. In other words, the hazards and delays in the transit of these vessels should be minimized in order to maximize the port's revenues.

For a port to be nautically accessible, it must meet the demand of sea-going vessels. This demand includes two main aspects. First, the dimensions of facilities: port infrastructure should be designed to accommodate vessels with maximum dimensions. Inadequately dimensioned port infrastructure precludes the accommodation of large vessels. Second, traffic capacity: the port network with its connected infrastructural components must be able to handle traffic volumes, as congestion reduces the availability of the infrastructure.

To maximize revenues in the short-to-medium timescales, port authorities primarily focus on optimizing the first aspect by assessing the vertical dimensions: the bed levels. The design of the bed levels results from the trade-off between nautical accessibility and dredging costs: the deeper the bed levels, the better the accessibility, but the higher the dredging costs, and vice versa. To reduce the bed levels in tidal ports, so-called tidal windows are often implemented. Tidal windows are periods of high (and calm) water during which deep-draughted vessels can enter or leave the port. By using tidal windows, the port can maintain acceptable port accessibility levels, while reducing required dredging efforts.

Various deterministic and probabilistic approaches for designing the bed levels exists in literature (Bos, Koop, and Bolt 2011; M. Vantorre, Candries, and Verwilligen 2014). These methods quantify accessibility as the number of accessible tides over the total number of tides for which they individually consider the deepest-draughted vessels in the fleet. As a consequence, they completely ignore the second aspect of nautical accessibility, namely nautical traffic. This aspect, however, is closely interconnected with the vertical dimensions of a port, and it can lead to cascading effects that reduce the accessibility and performance of the port. For example, if the bed levels are too shallow, the tidal windows for the largest vessels will be very narrow, which may lead to additional waiting times that in turn may prevent other smaller vessels, that could enter, from entering the port when priority handling policies for larger vessels are in effect. Therefore, the degree of nautical accessibility is typically overestimated in the currently applied design approaches for bed levels.

In this paper, we propose a method that can address both aspects of nautical accessibility. We apply the method to a simple test case of a liquid bulk terminal in the Port of Rotterdam, where we demonstrate the effect of tidal windows on nautical traffic. We show that this novel approach can lead to better insights into the trade-off between the actual accessibility or performance of a port and the dredging efforts as a function of the bed level design. Ultimately, this method is able to improve the design for bed levels, thereby maximizing port revenues.

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BACKGROUND

The bed levels and prevailing (and often varying) water levels determine the water depths within a port. However, these water depths cannot be fully exploited, as this would result in a high risk of a vessel running aground. This occurs when the actual draught of a vessel is greater than the actual water depth. To prevent this, a method reported by PIANC (2014) is frequently used which applies safety margins to these quantities. Its basic components are visualized in Figure 1 and are explained in the next section. Hereafter, two current design approaches for bed levels are presented that use this method and which are widely applied by port authorities.

PIANC guidelines

The PIANC (2014) approach prescribes a minimum under-keel clearance (UKC) to be kept for each vessel. This Gross UKC is the difference between the measured draught of the vessel with respect to a specific maintained bed level (MBL), also called nautical guaranteed depth (NGD). The MBL is dependent on the design bed level. Hence, the design bed level may theoretically follow directly from the Gross UKC and the measured draught of the deepest-draughted vessel. However, a design water level should be established for this purpose, which can be chosen as the minimum water level over a period during flood tide. These three components (i.e. MBL, UKC, and design water level) are discussed in the remainder of this section.

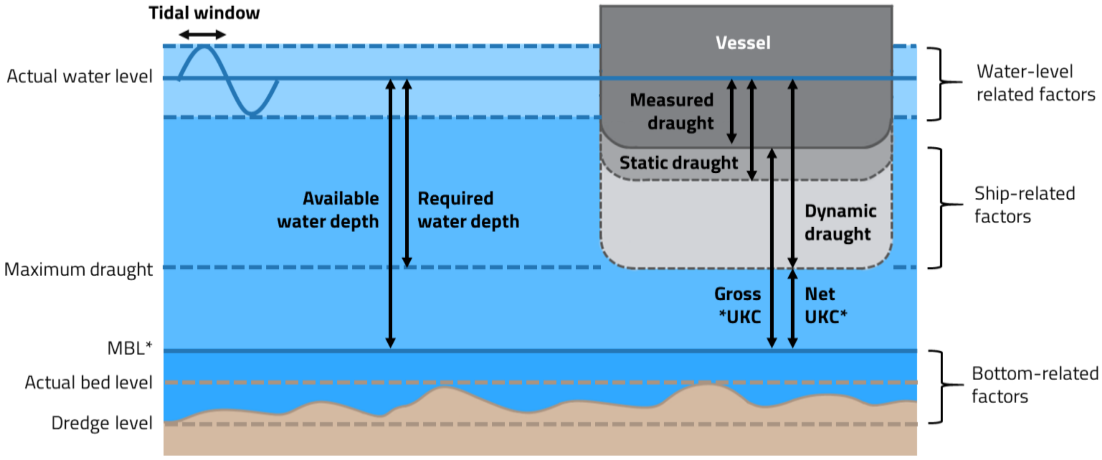

Figure 1 – Overview of the relevant parameters in the design of the maintained bed level: *UKC: Under Keel Clearance, MBL: Maintained Bed Level (by F.P. Bakker is licenced under CC BY-SA 4.0).

Maintained bed level

The MBL is a fixed level that is guaranteed to be above the actual bed. It equals the channel dredge level corrected by some safety margins. These are allowances that account for uncertainties in bottom-related factors, such as dredging, surveying, and sediment conditions. Additionally, there is a maintenance margin that provides a buffer for the sedimentation between dredging works.

Under-keel clearance

A Gross UKC is applied to the static draught of a vessel to account for variations in the actual draught of the vessel. The static draught refers to the lowest level of the hull of a stationary vessel with respect to the level of calm water. The UKC is composed of a static and a dynamic component. It includes multiple margins that compensate for ambiguities in these components. The static draught of a vessel is measured in salt water. A margin is applied that allows for uncertainties in the determination of this static draught (e.g. hogging and sagging). Furthermore, the static draught of a vessel can change over its route, as it is affected by the buoyancy of the water. This buoyancy can vary due to differences in salt concentration and water temperature. An extra margin is required to account for this, which is called the freshwater allowance (FWA).

In addition, the dynamic draught is dependent on the complex interactions of a moving vessel with its surroundings (e.g. wind, hydrodynamics and infrastructure). These dynamics influence the motion of a moving vessel, and thereby its draught. Examples include motion responses due to waves, vessel-waterway interactions (e.g. squat and dynamic trim), and wind and turning (e.g. dynamic list and heel). Extra margins are added to account for these motions. Finally, an additional allowance, called the Net UKC, is applied. This component may be dependent on the type of sediment and vessel, as well as the environmental consequences of a vessel hitting the bed. The Gross UKC is the sum of all these margins. It must be greater than a certain manoeuvrability margin (MM), which ensures that a vessel has adequate manoeuvrability. According to PIANC (2014), the MM is the difference between the available water depth with respect to the MBL minus the static draught and the dynamic components of heel, squat and trim.

Design water level

Water levels are subject to fluctuations that must be taken into account. These are mainly caused by waves, tides and meteorological influences, such as surges and seiches. The additional margins can either be positive or negative. Allowances for seiches, waves and meteorological effects are commonly 'positive' (i.e. they lower the required bed level), as they cause water level depressions. In contrast, tides generally result in a 'negative' contribution to the bed level (i.e. they elevate the required bed level), since they increase the water level, albeit temporarily.

For the deepest-draughted vessels, port authorities tend to use the tide in order to allow for higher maintained bed levels and consequently reduce required dredging efforts. They establish so-called tidal windows, which are tidal intervals during which deep-draughted vessels can access or leave the port. A distinction can be made between vertical and horizontal tidal windows. Vertical tidal windows are periods during which a certain design vessel complies with the UKC policy, in other words periods of sufficient water depth. In addition, the strength of tidal (cross-) currents during this interval should be limited to allow the vessel to safely manoeuvre into a port basin. The resulting accessible windows are further limited to the conditional periods of high and calm water that generally occur around high water slack (HWS). Thus, these tidal windows reduce the expenditures of port authorities and keep the port accessible for deep-draughted vessels.

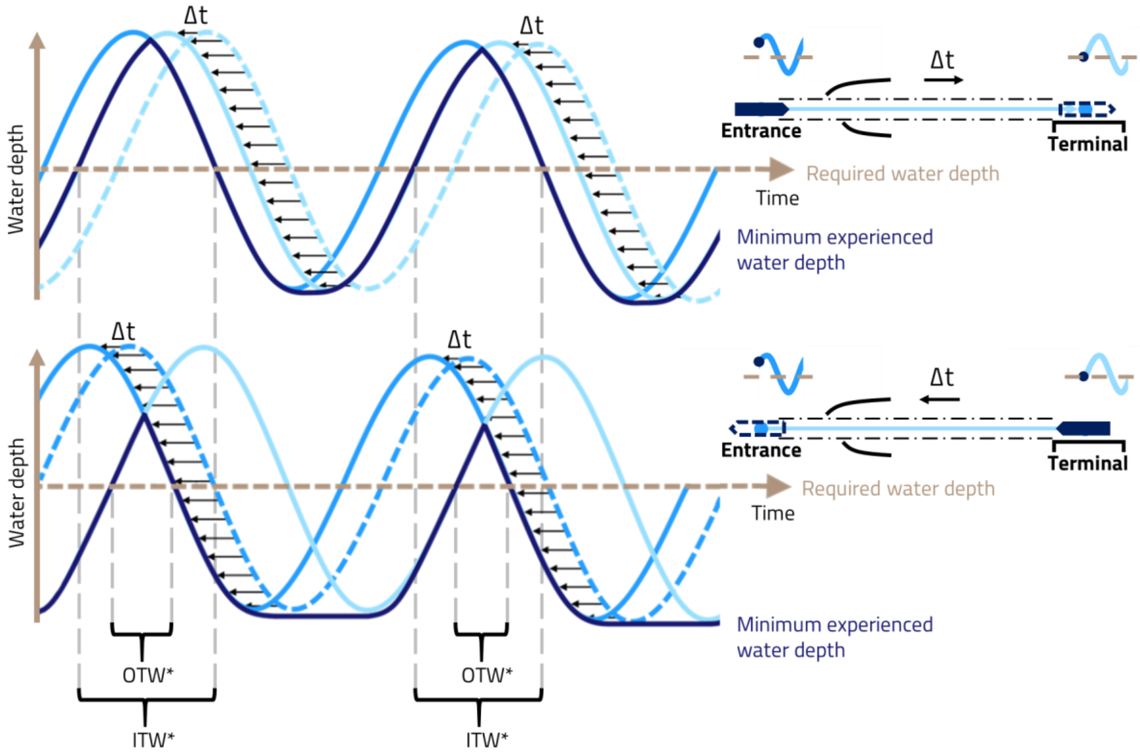

Figure 2 – The calculation method for tidal windows as applied in the current design approaches for bed levels: *ITW: Inbound Tidal Window, OTW: Outbound Tidal Window (by F.P. Bakker is licenced under CC BY-SA 4.0).

Current design approaches

Bed levels are generally designed based on the condition that the deepest-draughted vessels are prevented from hitting the bottom. Therefore, port authorities adopt the conservative design approach of PIANC (2014) that prevents the actual maximum occurring draughts to be greater than the minimum present water depths. These conditions need to hold over the entire route of the vessel. Hence, to apply this approach, port authorities need to know the hydro-meteo conditions and the established MBL for this route. Furthermore, the time at which the vessel will pass certain sections of the waterway needs to be estimated in advance. This results in different opening and closing times of particular sections of the waterway, from which the governing tidal windows can be calculated (see Figure 2). By applying this method we observe that outbound vessels experience shorter tidal windows than inbound vessels. This is caused by the tidal dynamics: an outbound vessel experiences a shorted high water as it sails against the direction of the tide. For this purpose, hydrodynamic forecast models are used. Two different design approaches for bed levels are found in literature: deterministic and probabilistic design approaches.

Deterministic

A deterministic approach uses static values for the safety components in the calculation of the UKC. The values are often a minimum Gross UKC or a percentage of the vessel's draught. They are generally based on pilot's experiences during the most unfavourable conditions regarding the water levels and actual draught of the largest vessels. These conditions, however, may only occur infrequently. As a consequence of this conservative design approach, bed levels are frequently over-dimensioned. This may lead to port areas with excessively deep MBLs and consequently less profit for the port.

Probabilistic

Probabilistic approaches determine the risk of bottom contact based on the product of the probability, resulting from a certain return period, and the consequences. Accessible time windows are then defined based on periods during which the risk of bottom contact is acceptable over the entire route of the vessel. Three predefined safety criteria exist (Savenije 1997; M. Vantorre, Candries, and Verwilligen 2014):

- Single transit bottom touch criterion:
  A criterion that prevents a vessel from touching the bottom, depending on the actual governing hydro-meteo conditions.
- Manoeuvrability criterion:
  A criterion that ensures that the vessel is capable of manoeuvring. It is based on the MM.
- Long-term vessel damage criterion:
  A criterion that prevents a certain percentage of maximum minor damage to the waterway in terms of risk (probability times consequences). The probability is derived from a certain acceptable return period. The consequences depend on the expected damage to the vessel, and the resulting damage to the economy and the environment. This results from the type of vessel, the type of channel, the bottom material, and the surrounding ecosystem.

In principle, the long-term vessel damage criterion is governing. However, in the case of favourable conditions, the manoeuvrability criterion overrules the damage criterion.

To apply the probabilistic method, estimates of the vessel motions must be made for different vessel speeds and hydro-meteo conditions. Uncertainty is applied to the bed level, the static draught and the dynamic draught components of the vessel. The uncertainty in the dynamic component is mainly due to uncertainties in the actual and forecasted hydro-meteo conditions. Different methods can be applied to quantify these uncertainties, such as frequent surveys, vessel response prediction based on towing tank experiments and in-situ measurements, and real-time GPS measurements (Marc Vantorre et al. 2008; Parker and Huff 1998). Since the dynamic response depends on the vessel characteristics (e.g. shape of the hull, height of the vessel, loading degree, etc.) the method should be applied to a selection of the deepest-draughted vessels (Bos, Koop, and Bolt 2011; M. Vantorre, Candries, and Verwilligen 2014). The method results in a risk-based dynamic UKC policy, DUKC (Curtis 2018). In general, the probabilistic method offers the possibility to apply shallower MBLs.

Problem statement

By focusing on the UKC of individual vessels, current design approaches completely ignore the cascading effects between vessels. These arise from causality and the interactions between vessels and the port infrastructure, which has a limited capacity. For example, a deep-draughted vessel with a very restrictive tidal window and priority over other vessels may impose limited accessibility for smaller vessels. The large vessel may have to wait to enter the port, causing delays during arrival, and may also have to wait to leave the port, occupying the terminal. This results in additional waiting times for smaller vessels and, hence, less accessibility for these vessels, while not being subjected to tidal windows individually. Consequently, current methods may lead to excessively shallow MBLs. Additionally, they do not account for vessel encounters and overtakings, which can temporarily increase the actual draught. Hence, interactions between vessels cannot be neglected.

METHOD

To include vessel interactions and better quantify nautical accessibility, we developed a nautical traffic model based on the Python package of OpenTNSim that was developed by Delft University of Technology (Baart et al. 2022). OpenTNSim is an open-source discrete-event simulation model that can be generically used to investigate the mesoscopic behaviour of port and waterway networks. This mesoscopic level is of particular interest for problems that simultaneously require a large study area and more detailed engineering models to quantify specific aspects of the network or of the agents using it (Van Koningsveld et al. 2021). Hence, it is very suitable to investigate the effect of chosen design MBLs in a port. The remainder of this chapter describes the nautical traffic model in more detail.

Nautical traffic model

OpenTNSim is built upon the discrete-event simulation package of SimPy. It works according to the following principles, which are made specific for our study:

1. The behaviour of the active components (vessels) is modeled with processes:
   The processes are defined by Python's generator functions. These functions generate time steps in the model, namely when an event starts or stops. An example is a "timeout" generator with a certain predefined step time. This can be used to simulate an (un)loading event of a vessel, equal to the (un)loading time.
2. All processes live in an environment:
   The environment assembles all processes and puts them in the same timeframe. For example, two vessels with different (un)loading times can be (un)loaded simultaneously.
3. The processes (vessels) interact with the environment and with each other via events:
   Events are process functions that can interact with other events, and thus with other components. For example, SimPy is able to model a vessel that is waiting for another vessel to finish (un)loading (see next section).

Simpy has shared resources with a limited capacity, which can be triggered by events. These resources can represent port infrastructure. There are three categories:

1. Resources:
   These can be used by a limited number of processes at the same time, which corresponds to their capacity. When all slots are taken, new requests of processes are queued. Once a user request of a process is released, a pending request will be released. Terminals with jetties (e.g. liquid bulk terminals), turning basins and anchorage areas can be modelled as resources, as they have a finite integer number of capacity. For example, when a terminal with one jetty is occupied, no other vessel can use the terminal. A request can have a priority and can also be pre-emptive, meaning that it can override a previously granted request.
2. Containers:
   These contain up to a capacity of matter which can either be continuous or discrete. They support requests to place and remove matter into/from the container. If there is insufficient capacity left to place new matter or if there is insufficient amount of matter left to be removed, a new request will be queued. With this content, infrastructures with a given length can be modelled, such as terminals with quays (e.g. dry bulk and containers terminals). For example, a quay with a length of 300m that is claimed by a vessel of 200m cannot be claimed by another vessel of 200m.
3. Stores:
   They allow for the production and consumption of Python objects, rather than an amount of matter as in the case of containers. Stores are not included in the nautical traffic model and are therefore not discussed in further detail in this paper.

The model uses discretization in both time and space. These aspects of OpenTNSim are illustrated in Figure 3a and Figure 3b, respectively. It shows the spatial outcome of a specific time step, t6, in the timeline of a discrete event simulation of two vessels requesting the same terminal with a unit capacity. The large vessel arrived earlier and made a request for the terminal. However, as it made a request to enter the port, it was instructed by vessel traffic services (VTS) to wait in the anchorage area for a tidal window, as the required water depths were insufficient at that time. At flood tide, the large vessel receives permission to enter, and subsequently leaves the anchorage area and proceeds to the terminal. During this transit, a smaller vessel arrives at the port and requests access to the terminal. This vessel is not subjected to the tidal windows, but must wait until the terminal becomes available.

Vessels

Vessels are included in the model as agents that can move in space over time. Specific information can be coupled to the agent, such as its route, its vessel characteristics (e.g. draught) and vessel speed over the edges of the network. During the simulation, we can keep track of the time and location of the vessel.

Spatial discretization

OpenTNSim uses the open-source NetworkX package to model the port network. This package is able to construct a transport graph and to select routes based on criteria. Such a graph consists of nodes and edges to which infrastructure, schematized by the shared resources of SimPy, can be assigned. In Figure 3b, we added an anchorage area to node II, a turning basin to node IV and a terminal to node V. We can give geographical information to the graph through the Geospatial Data Abstraction Library (GDAL). This enables us to calculate the distances between the nodes, and the positions within an edge. Additionally we can provide the graph with MBLs, UKC policies, and hydro-meteo conditions based on hydrodynamic models.

Time discretization

OpenTNSim uses a discrete event system specification to discretize time. Instead of a regular time step, the time steps in the model are variable and defined by the events themselves, meaning that we only get output when events start or stop. This is illustrated in Figure 3a. Herein, the specific events that determine the time steps are: sailing, waiting and (un)loading. These are further elaborated in the next subsection.

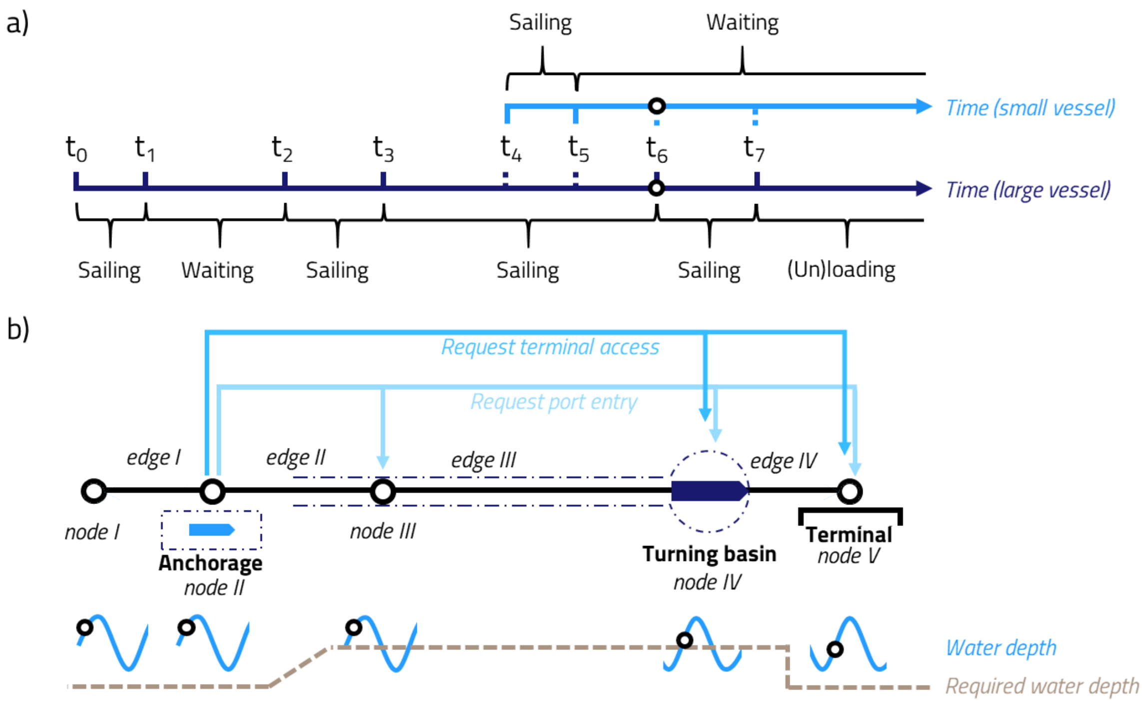

Figure 3 – Overview of the time (a) and spatial (b) discretization in OpenTNSim (by F.P. Bakker is licenced under CC BY-SA 4.0).

Events

The behaviour of the vessels is modelled with events that can use the information of the vessels and the network. The following events are modelled:

- Sailing
  This is modelled using a timeout event that is assigned to a vessel to pass an edge. Since we assume that we know the speed of the vessel over the specific edge, we can calculate the sailing time based on the distances between the nodes. After the event, the vessel's location information is updated to match the location of the end node of the edge.
- Requesting terminal access
  When a vessel arrives near the anchorage area, it requests the resource that represents the terminal. When the terminal is occupied, SimPy is able to determine the waiting time of the vessel, namely the difference between the start time of the waiting event and the time when the user request of the terminal is released. After the completion of this event, the vessel can leave the anchorage area. As mentioned above, a request can be pre-emptive, allowing to take priority over an earlier granted request.
- Turning, (de)berthing and (un)loading
  By knowing the size and loading degree of the vessel, we can estimate the time it takes for a vessel to turn in the turning basin during its return trip, the (de)berthing time, and the (un)loading time. These are modelled by a timeout event required to pass these infrastructures.
- Requesting port entry
  The tidal window calculation is based on an event that includes the deterministic approach for calculating the minimum required available water depth, as mentioned in Section 2. If a tide-bound vessel arrives outside of a tidal window, the event gives the vessel a waiting time equal to the difference between the current time and the starting time of the next forecasted tidal window, and directs it to the anchorage area. The event must be completed before leaving the anchorage area. It operates as the VTS of a port.

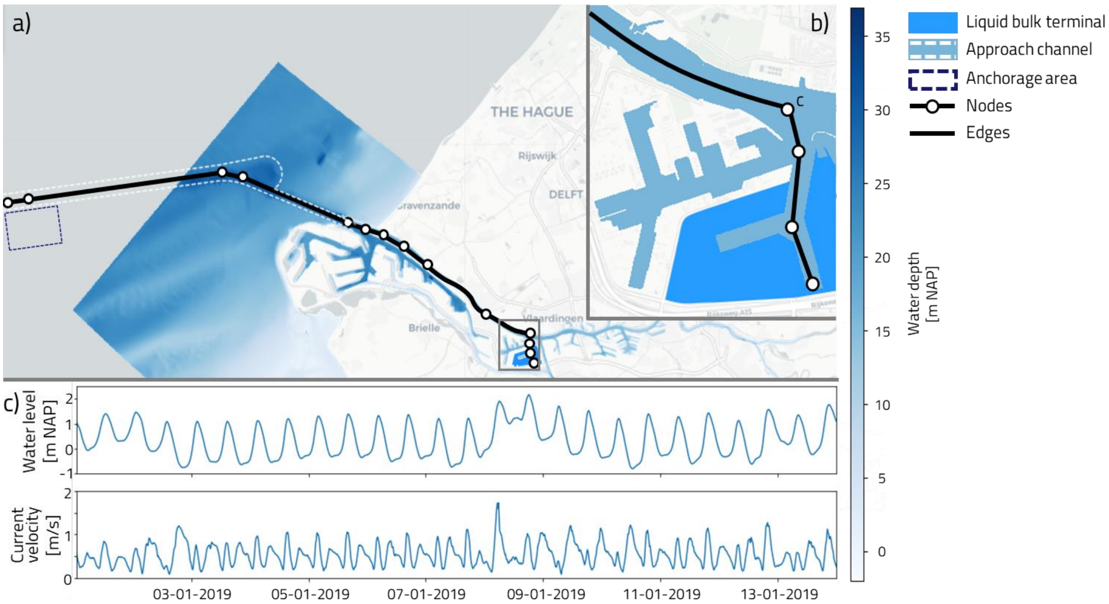

Figure 4 – Overview of the case study of the liquid bulk terminal in the Port of Rotterdam (a), with a close-up at the harbour basin of the liquid bulk terminal (b), including the water level and current velocity data (c) at the entrance of the harbour basin (node c) (by F.P. Bakker is licenced under CC BY-SA 4.0).

Model set-up

The nautical traffic model is used to simulate a case study of a liquid bulk terminal in the Port of Rotterdam. This terminal is located in the 3rd Petroleum Harbour, situated along the main waterway, the Nieuwe Waterweg (see Figure 4). The model requires the following input:

- Network
  The graph of nodes and edges follows the entrance channel from the anchorage area to the liquid bulk terminal. It was derived from Rijkswaterstaat's Fairway Information Services (FIS), which includes geographical information, along with other data.
- Infrastructure
  The following infrastructure is added to the graph: an anchorage area (on an offshore node at 25 km from the start of the entrance channel), a turning basin on a node in the harbour basin (at a distance of 150 km from the start of the entrance channel), and a terminal at the final edge of the route (between 152 and 154 km from the entrance channel). There is a unit capacity at the turning basin and terminal, while the capacity of the anchorage area is unlimited.
- UKC and hydrodynamic data
  The nodes are enriched with predefined MBLs, and UKC and FWA policies. Furthermore, water levels and current velocities are assigned to the nodes, which are obtained from a numerical model. The Nieuwe Waterweg has an MBL of 16.4 m NAP. The Gross UKC policy prescribes a clearance of 10% of the ships draught with respect to the MBL. Additionally, the FWA initially equals 1.0% of the ships draught, which increases to 2.5% after a distance of approximately 14km from the heads of the breakwaters (de Jong 2020). The entrance channel and the harbour basin do not impose draught limitations. At the entrance of the harbour basin, there is a horizontal tidal window for all vessel as entry is prohibited when the current velocity exceeds 1 knot.
- Vessels
  Two large long range (LR) tanker vessels are modelled: an LR1 and a larger LR2 vessel with a static draught of 12.2 and 15.0 meters, respectively. Both vessels have a speed of 9 knots and an (un)loading time of respectively 3.8 and 4.7 days, which was derived based on Automatic Information System (AIS) data. The LR2 vessel is subject to a vertical tidal window, while the LR1 vessel has no water depth limitations.

We consider a situation where the LR2 vessel arrives on the first day of the simulation and the LR1 vessel arrives at the fifth day. Two scenarios are run:

1. No congestion due to tidal windows
   A situation where the LR2 vessel is not subject to a tidal window; it arrives at a time that falls within a tidal window, and finishes (un)loading at a time that falls within a tidal window.
2. Congestion due to tidal windows:

A situation where the arrival times of both vessels (LR1 and LR2) are delayed by the same time such that the arrival time of the LR2 vessel is outside of a tidal window, which causes the preferred departure time to be also outside of a tidal window.

For simplicity, we take the waiting times of the vessels as the performance parameter of interest.

RESULTS

The model results in a time-distance diagram, as presented in Figure 5a. The background colours indicate the maximum allowable draught at a given location over time. They correspond to the water depths at the nodes (see Figure 5c). The horizontal tidal restriction results in additional tidal windows (see Figure 5b). These periods correspond to the times when the current velocity restriction is not exceeded (see Figure 5d).

No congestion due to tidal windows

In Figure 5, we see that the LR2 vessel arrives during a rising tide when there is a tidal window. The vessel requests access to the terminal, which is granted since it is not occupied. Furthermore, vessel LR2 requests to enter the port, which is also granted as it is possible to have a safe transit. Therefore the vessel can immediately proceed to the terminal, where it will be (un)loaded for 4.7 days. At the moment when the (un)loading is almost finished, the LR1 vessel approaches the port. It is able to request access to the terminal with pre-emption, as the LR2 vessel will have left the terminal once the LR1 vessel arrives (when vessel LR2 finishes (un)loading, its request to leave the port can be granted as there is a tidal window). Therefore, the request for the terminal access of vessel LR1 is accepted and also the request for port entry is granted, as the vessel arrives within a horizontal tidal window (recall that it does not have a vertical tidal window). Hence, vessel LR1 arrives at the terminal and starts (un)loading for 3.8 days. Once it finishes (un)loading, it requests to leave the port, which is granted as it falls within the horizontal tidal window. Therefore, it releases its request for terminal access, making the terminal available again. In this scenario, we observe that there is no waiting time for either vessel.

Congestion due to tidal windows

When we simulate the same scenario but with a slightly delayed arrival time for both vessels, waiting times will emerge, as can be seen in Figure 6a. First, there are waiting times for vessel LR2 due to draught limitations. As the arrival time is outside of a tidal window, the request of vessel LR2 for port entry cannot be granted by VTS. Later, after the vessel finishes (un)loading, its request to leave the port cannot be granted either, because the time of the request is outside of a tidal window again. It waits for the rising

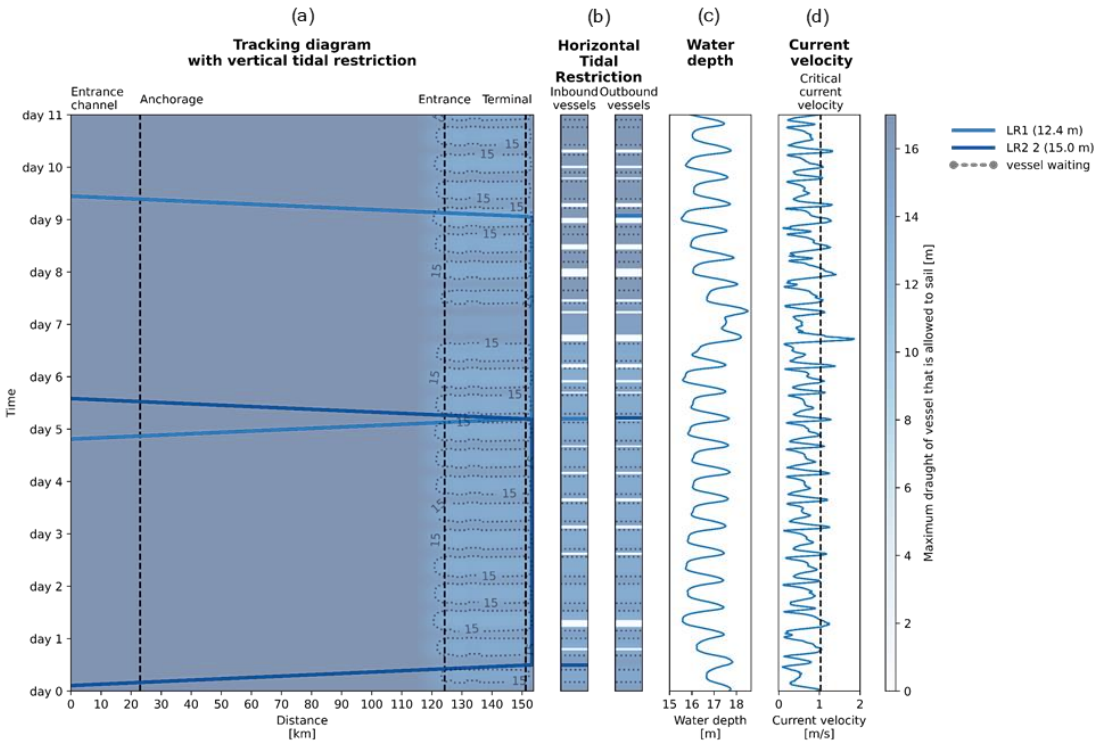

Figure 5 – Results of the simulation run without influence of tidal windows: a time-distance diagram (a), the horizontal tidal restriction (b), water depth (c), and current velocity (d) near the harbour basin of the liquid bulk terminal (by F.P. Bakker is licenced under CC BY-SA 4.0).

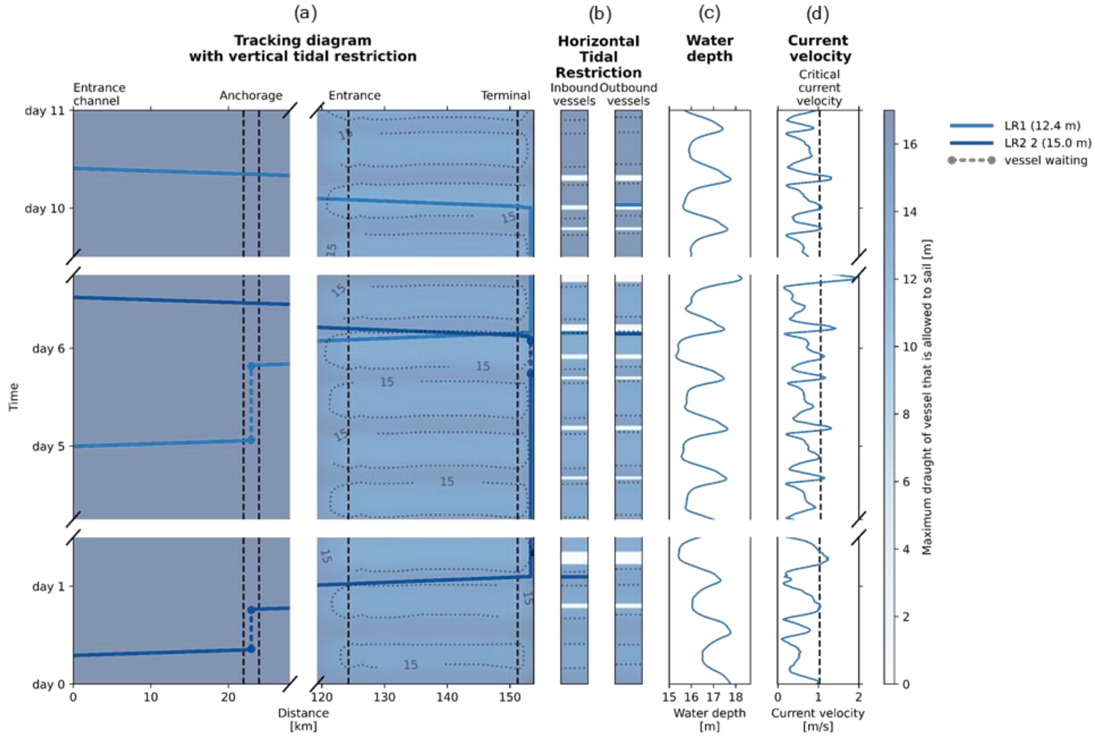

Figure 6 – Close-up of the results of the simulation run with influence of tidal windows: a time-distance diagram (a), the horizontal tidal restriction (b), water depth (c), and current velocity (d) near the harbour basin of the liquid bulk terminal (by F.P. Bakker is licenced under CC BY-SA 4.0).

tide to be guided through deeper water (between the contour lines of the maximum draught of 15 m). Second, due to the further delayed arrival and departure of vessel LR2, there is congestion-related waiting time for vessel LR1, as its request to access the terminal cannot be granted since it is occupied by vessel LR2. Hence, it has to wait in the anchorage area until it is able to pre-empt the request for terminal access by LR2. In total, vessel LR2 had to wait 9.8 hours before it could enter the port, and 7.3 hours before it could leave the port, equalling the 17.1 hours of waiting time for vessel LR1 (see Table 1).

Table 1 – The waiting times of vessels LR1 and LR2 as a consequence of the tidal windows.

Vessel	LR1	LR2
Waiting in anchorage [hours]	17.1	9.8
Waiting at terminal [hours]	0.0	7.3
Total	7.1	17.1

DISCUSSION

We have seen that the waiting times can increase significantly, depending on the moment of arrival of the vessels. This is due to the narrow tidal windows for vessel LR2. While vessel LR1 is not subject to tidal windows individually, it is still affected by the cascading effects of the other vessel. We have also seen that tidal windows can lead to extra congestion due to causality. The additional waiting time on arrival of vessel LR2 lead to additional waiting time on departure. Considering these cascading effects, we have shown that nautical traffic capacity and bed level design are interconnected. Hence, bed level designs that are solely based on individual vessels may be suboptimal.

Proposal of a new port performance indicator

The results further indicate that it is highly debatable whether a bed level design should be the result of the trade-off between dredging costs and nautical port accessibility. Nautical port accessibility is deemed a very suitable and accurate indicator of port performance when applying current design approaches. This is because it is most important for the deepest-draughted vessels to be able to enter or leave a port during a tidal cycle. However, in the case of the newly proposed model, the degree of downtime, the percentage of time a port is inaccessible, may be more applicable. Yet, the degree of downtime is highly dependent on the arrival patterns of vessels and the nonlinear interactions between the vessels themselves, and the infrastructure. Therefore, a probabilistic parameter based on total waiting time divided by turnaround time would be more appropriate. This parameter can be subjectively weighted to give more weight to the larger vessels that generate more revenues for a port.

Improvements and opportunities of the nautical traffic model

Only a simple case study has been presented in this paper. However, the model is well-capable of researching more complex situations. Various case studies involving a fleet of vessel of different types that call at a port with multiple terminals, anchorage areas and turning basins are currently researched. Furthermore, complex tidal window policies and traffic regulations are being included in the model. Extensive calibration and validation work is also being carried out based on an elaborate analysis of shipping data, particularly Automatic Information System (AIS) data, to make more accurate and justified predictions. These developments allow the nautical traffic model in OpenTNSim to be applied for various other purposes based on various performance indicators related to capacity, efficiency, safety and sustainability. Examples include the optimization of nautical traffic policies and port infrastructure, and the impact of changes in the hydrodynamic system on nautical traffic and other non-port related stakeholder functions (Iglesias 2022).

CONCLUSION

This paper presents the application of a novel nautical traffic model that is able to optimize bed level designs in ports. Currently, bed levels are optimized based on a trade-off between dredging efforts and the port accessibility of individual deep-draughted design vessels. The new approach consists of a discrete-event simulation model in the open-source and generic Python package OpenTNSim. It allows the inclusion of the interaction between the nautical traffic dynamics of a fleet of vessels and the physical system, including bed levels. The results show that this interaction is inadvertently disregarded in current approaches, as the model found that these interactions can lead to significant cascading effects that reduce the nautical accessibility of the port; smaller non-tidal vessels are affected by the tidal windows of larger vessels during congestion of the port system. The effectiveness of nautical port accessibility as a performance indicator may therefore be debatable. Consequently, maintained bed levels based on the current design approach can be considered suboptimal. It is expected that further ongoing research with the nautical traffic model will lead to more accurate analyses of various nautical traffic policies and port infrastructure designs, which include bed levels designs.

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