Part II - Ch 3 Port layout

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3 Port layout

An essential part of port planning is a well designed layout of port. This chapter discusses the dimensioning of port water areas, the guiding principles of port layout development and the functional design of port terminals. In general, the sequence of the use of rules and models during a design should be: use of (1) rules-of-thumb and PIANC manuals, (2) fast time simulation models and simple capacity models, and (3) real time simulation models, sophisticated capacity models and nautical safety analysis models. The rules presented here are for a first design, for example in the (pre-)feasibility stage. The models in Steps 2 and 3 can be used in the conceptual design phase and the final design phase respectively, and will be discussed in Part III – Section 2.5.

3.1 Port water areas

Port water areas are those water areas that are used by vessels calling at and operating in and from the port (tugs, pilot vessels, service vessels). They determine to a large extent the port layout and their proper design can make a large difference in investments and operational costs.

If the natural water depth is not sufficient for safe access of the largest vessels, for instance, or if sedimentation is about to reduce the navigable depth to that point, dredging is required. This can lead to substantial costs for capital and maintenance dredging. Optimising port water areas for less dredging can therefore save significant costs. On the other hand, smooth access by providing sufficient space to manoeuvre increases the port's efficiency and service level. The port design needs to balance these potentially conflicting aspects.

To properly design port water areas, the behaviour of their users, in this case the vessels, needs to be known. An ocean-going vessel visiting a port normally goes through the following steps:

- Vessel calls at the port 24 hrs in advance.
- When approaching the port it reduces speed.
- A pilot comes aboard.
- The pilot takes over control of the vessel and communicates with the tug master who will assist manoeuvring once the vessel has entered the port.
- Vessel enters the port and further reduces speed.
- Tugs connect and assist the vessel to come to a full stop.
- The vessel turns assisted by tugs.
- Tugs assist the vessel to approach the designated berth.
- Berthing, connecting lines.
- Cargo transfer.
- Deberthing.
- Tugs assist the vessel to the access channel for departure.
- Vessel leaves the port.
- Pilot disembarks.

Each of the above steps has operational requirements that need to be considered when designing the port layout and may involve operational restrictions leading to downtime of the port. Port water areas include (Figure 3.1):

- *Pilot boarding areas* – pilots usually board outside of the port limits, at the latest when the vessel enters the outer access channel.
- *Anchorage areas* – here the vessels wait until they can enter the port, or for new instructions from the shipping line.
- *Outer access channel* – a marked navigation channel outside the shelter of breakwaters; in case of insufficient water depth it requires capital and maintenance dredging.
- *Inner access channel* – the sheltered part of the channel, (often) protected by breakwaters; here vessels will slow down and tugs will assist them to come to a full stop.

- *Turning basin* – space where the vessels can be turned in the direction that gives access to the berth.
- *Berthing areas and port basin* – sheltered areas where vessels are manoeuvred and moored to the quay.
- *Other areas* – such as a tug and marine pilot base and river barge waiting and berthing areas.

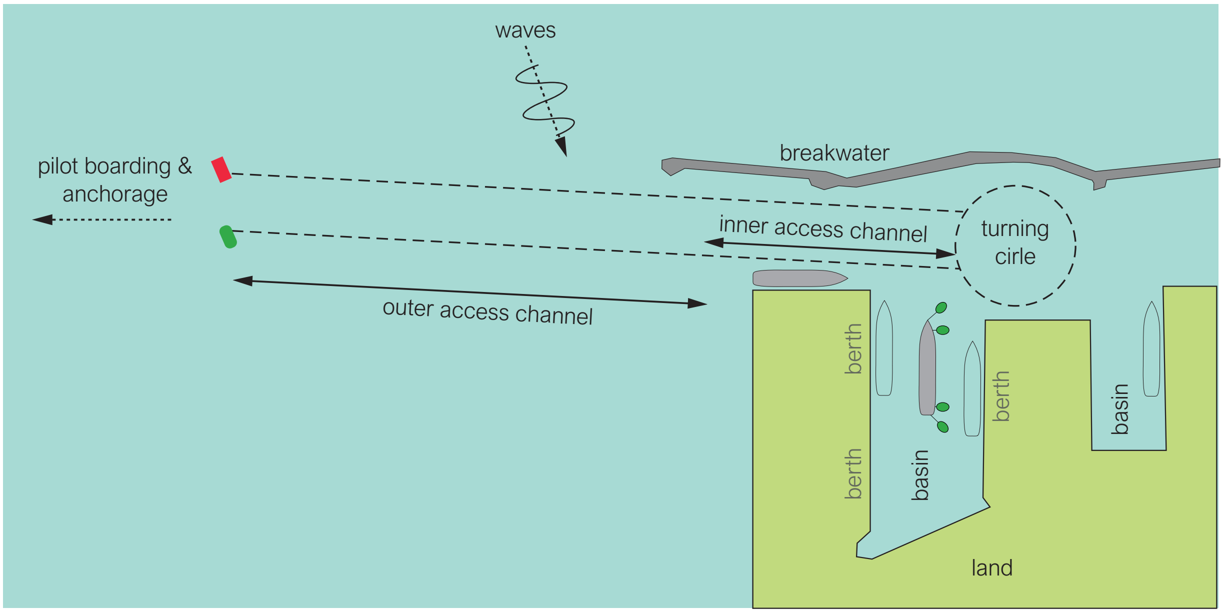


Figure 3.1: Port water areas; pilot boarding and anchorage are further offshore (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

In the next section we explain the operational procedures when a vessel enters the port and how these will have to be accommodated in the port layout. For further details we refer to PIANC (2014d) and Part III – Section 2.3.

3.1.1 Port entrance and departure procedure

Pilot boarding

Pilots will generally board a ship via a SOLAS (Safety of Life at Sea) compliant ladder and boat (Figure 3.2, left). Pilot boarding may become unsafe in high seas and therefore the ship may provide additional lee to the pilot boat, typically for wave heights exceeding $H_s > 1.5$ m. An area of sufficient size is required to enable a vessel to manoeuvre safely and provide an acceptable lee for the transfer under all probable headings, dependent on the prevailing local meteorological conditions (PIANC, 2014d). Unless at anchor, the vessel will sail at a speed of about 6 to 12 knots and, depending on the ship and prevailing conditions, may be required to maintain this heading and speed for up to 10 to 20 minutes. The ship master may not alter the vessels heading until the pilot is on the bridge and has interacted with the master. As a result, a pilot may have to access the vessel more than 5 km away from the outer access channel (PIANC, 2014d). Pilot boarding by boat under heavy wave conditions (e.g. $H_s > 3$ m) may be dangerous; boarding by helicopter may be an alternative (Figure 3.2, right). This can be done under most wave conditions and for wind speeds up to 55 knots (> 10 Beaufort). The pilot usually leaves the ship inside the port area and can safely use ladder and boat there.

Tug assistance and control

Large ocean-going vessels have limited control at slow speeds, so that tug assistance is required to safely manoeuvre inside the port. The tug configuration, number of tugs and total bollard pull required are normally based on a pilot's experience and circumstances such as the port layout, environmental conditions, the size of the calling vessel and its manoeuvring facilities (e.g. controllable pitch propellers, azipod propellers, bow and stern thrusters).

Figure 3.2: Pilot boarding; left: by boat and ladder (Shipping pilot by www.pikist.com is licenced under CC0 1.0); right: Pilot boarding a vessel by helicopter (by Hokewiki is licenced under CC BY-SA 3.0).

Depending on the port, vessels above a certain size can be obliged to use tugs. Table 3.1 presents the total bollard pull and the number of tug boats for dry bulk carriers, according to the formula (see Hensen, 2003, who also describes more elaborate models):

$$T_B = 6 \cdot 10^{-4}\Delta + 40 \text{ [ton]} \tag{3.1}$$

where Δ is the ship displacement in tonnes.

Vessel	L_{OA} **(m)**	Δ **(ton)**	**Total bollard pull (ton)**	**Nr. tug boats (50 ton BP each)**
5,000 DWT	90 – 125	5,000 – 6,000	44	0 – 1
15 – 20 kDWT	150 – 210	19,000 – 32,000	59	1 – 2
Handymax	175 – 230	47,000 – 66,000	80	2
Panamax	220 – 260	70,000 – 110,000	106	2 – 3

Table 3.1: Number of tug boats required for different classes of dry bulk carriers (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The environmental limits up to which tugs can pick up lines and provide assistance to the vessel approaching the port depend on the combined environmental conditions (waves, currents and wind), the experience of the crew, the size of tug boats and whether the tug can operate on the more sheltered leeside of the ship. The limiting current speed is in the order of 5 to 6 knots and the limiting wave height for tug operation is in the range of H_s = 1.5 to 2.0 m, whereby under specific conditions higher wave limits can be allowed, for instance for leeside tug operations. This means that outside the area protected by breakwaters, wave conditions are often too severe for the tugs to operate.

3.1.2 Nautical areas

Outer access channel

Once the pilot has taken over control of the vessel, it approaches to the port at a speed, V_s, through the outer access channel, which is marked by buoys. Tug assistance in the outer channel is often not feasible, as the vessel speed is too high and the waves are too high to secure the tugs to the ship and assert control. Before entering the breakwater-protected zone, the vessel slows down to the minimum speed at which it can keep a steady course without the assistance of tugs. See Part III – Section 2.3 for further details.

Inner Access Channel

Once the vessel is fully behind the breakwater it further reduces its speed to enable tugs to come alongside and pick up lines to make fast (Figure 3.3; also see Part III – Section 2.3). While the tugs are fastened, the vessel maintains its speed. Once the tugs have been fastened, they can exert forces to control the vessel. Using its own engines (power astern) the vessel will further slow down and come to a complete stop. The tugs generally stick to controlling the vessel's heading and position.

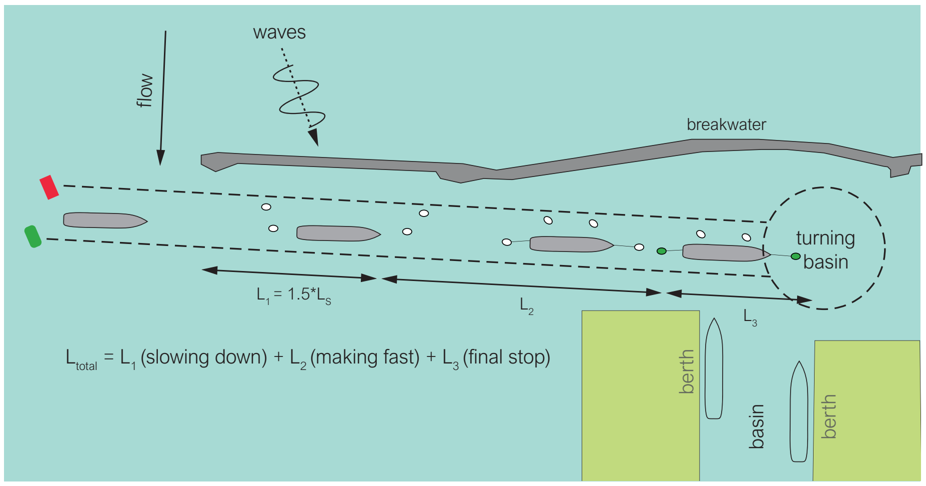


Figure 3.3: Deceleration and stopping procedure upon port entrance (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The total stopping distance of a ship depends on factors such as the initial ship speed, the displacement and the installed propulsion power. As first approximations, the distances needed for a vessel to come to a full stop are: $3 \div 5\ L_{OA}$ for ships in ballast, $7 \div 8\ L_{OA}$ for fully loaded ships. If the port entrance is often exposed to severe environmental conditions, the stopping distance should typically be measured from the beginning of the sheltered area to the centre of the turning basin. For large vessels this may mean access channel lengths of more than 2 km, i.e. to a considerable length of the (expensive) breakwaters. See Thoresen (2018) for further reference.

Measures to reduce this length may save significant amounts of investment costs in breakwaters and dredging, but have to be operationally safe. Additional simulation tests would therefore be necessary as part of the design process. Possible improvements include:

- Tugs make fast beyond the sheltered area. This can only be done if the environmental conditions permit. Large tugs with higher operational limits, or accepting downtime during storm conditions, are options to be considered in that case.
- Tugs pick up lines beyond the sheltered area without making fast. They start making fast as soon as the vessel has entered the sheltered zone.
- Assignment of an ebb-tidal window, in order to have the vessel's entrance speed reduced by the opposite current.

Turning basin

The turning basin is the area where vessels turn, assisted by tugs, before being brought to their berths. The minimum diameter of the turning basin to be considered in the conceptual design phase is 2 L_{OA} of the design vessel. Adjustments can be made to account for drifting of the vessel in case of strong currents or winds, and for vessels in ballast. Vessels using the main propeller and rudder as well as the bow thrusters could do with a turning basin diameter of 1.5 L_{OA}. Where the ship is turned by warping around a dolphin or pier and usually with tugboat assistance under calm conditions, the turning diameter can be reduced to 1.2 L_{OA}. In small ports without tug assistance, however, the basin diameter should be at least 3 L_{OA} (PIANC, 2014d). Also see Part III – Section 2.3 and Thoresen (2018).

Inner channels

In a shallow channel a passing vessel can exert quite significant forces on another vessel moored alongside the channel, leading to high mooring line forces and vessel motions at berth. These effects are functions of the passing vessel's speed, its blockage coefficient A_s/A_c and the separation distance between the two vessels. In the conceptual design stage, the following guidelines apply:

- If the passing vessel's speed is 4 knots or less, the separation distance (hull side to hull side) should be at least 2 times its beam.
- If the passing vessels' speed is 6 knots or more, the separation distance (hull side to hull side) should be at least 4 times its beam.
- For vessel speeds between 4 and 6 knots, the minimum separation distance can be interpolated.

In the detailed design phase a dynamic mooring analysis is advisable. This is the case especially if a berth with sensitive operations, such as container transfer, is located alongside a busy channel. A dynamic mooring analysis is advisable (see Part III – Section 2.3 and Part IV – Section 4.3).

Basin width

A port basin should be wide enough to enable vessels and tugs to manoeuvre. This generally leads to a proportionality with the vessel beam, with a proportionality factor depending on the type of vessel. Further see Part III – Section 2.3.

Berths

The space between berthed vessels depends on the vessel size, but also on the arrangement of the berths. Table 3.2 gives an overview of the distances recommended in Puertos del Estado (2007).

Anchorage

PIANC (2014d) defines an anchorage as the area where vessels drop anchor either awaiting entry into port or to undertake cargo handling, passenger transfer, bunkering or other cargo operations associated with that port. Anchorages are usually located in an outer harbour area or in the outer approaches to the port. However, under certain circumstances, anchorage area provision may be required within the working port area, for example if the port lies along the banks of a river.

Buoy moorings

As an alternative to fixed quay walls and jetties, a buoy mooring can be used. Especially in deeper waters, this may be a good option for the transfer of liquid bulk (mainly crude). Operational limits of buoy moorings are up to significant wave heights of 2.5 m, whence they can be used in open seas with a mild wave climate. Mooring on a buoy requires quite some space for manoeuvring, typically in the order of 1 km for very large crude carriers.

3.1.3 One-way or two-way channels

PIANC (2014d) states: 'Normally, the first choice for an approach channel is a one-way channel using the design ship with the maximum beam and windage. This is usually the most economical design for shorter channels with low traffic intensities. However, for longer channels and/or higher traffic intensity, two-way channels may provide a better design.'

The capacity of port approach channel(s) and manoeuvring area(s) depends on the required service level, in terms of acceptable waiting times and turnaround times. There are no widely accepted criteria for the acceptable waiting time, but practical indications are (PIANC, 2014d):

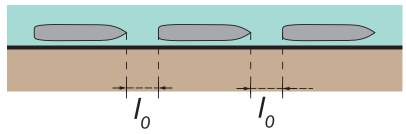
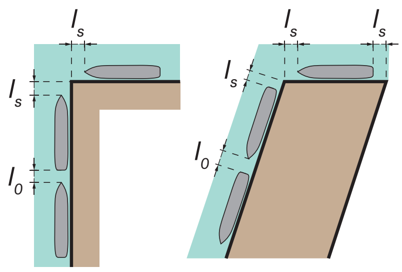
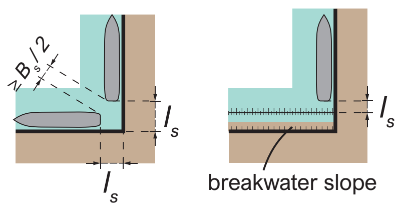
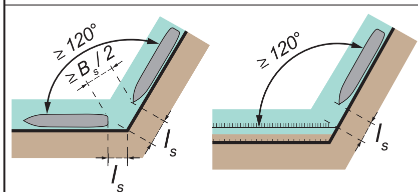
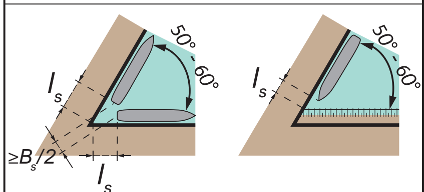
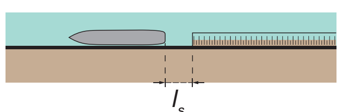
Dock Layout	Recommended distance between berths				
	L_s> 300m	201 - 300	151 - 200	100 - 150	< 100
	l_0 = 30m	25	20	15	10
	l_s = 30m	25	20	10	5
	l_s = 45m	30	25	20	15
	l_s = 30m	20	15	15	10
	l_s = 60m	50	40	30	20
	l_s = 20m	15	15	10	10

Table 3.2: Recommended berth distances for different dock layouts (reworked from Puertos del Estado, 2007, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

- container vessels: 5 – 10 % of the service time (time to unload and load a vessel),
- gas carriers: 10 % of the service time,
- general cargo vessels: 30 % of the service time,
- liquid bulk carriers: 30 % of the service time,
- ore carriers: > 40 % of the service time, and
- cruise vessels: 30 minutes.

At the start of a new port development traffic intensity will be low and a single-lane channel may be sufficient. When developing a master plan, however, one has to consider expected future intensities and reserve enough space to accommodate them. In the conceptual design phase the port approach system (access channel + turning basin) can be considered as a service system to which queueing theory can be applied to estimate waiting times and capacity requirements (see Figure 3.4 and Part IV – Section 2.3).

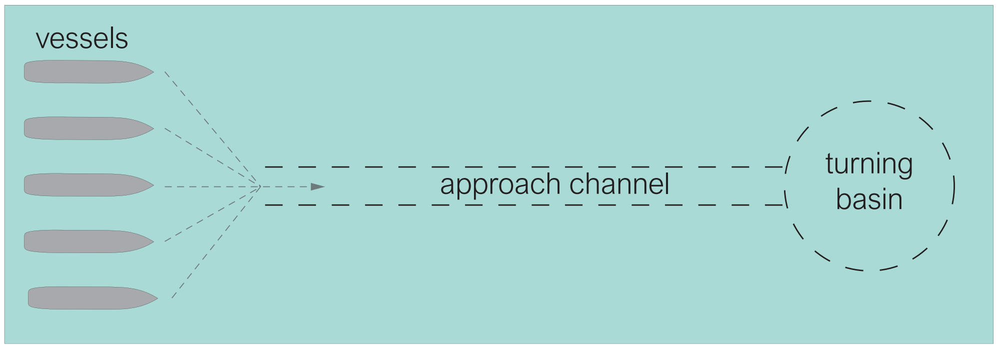


Figure 3.4: Port approach system considered as a service system in queueing theory (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Since the part of the chain with the least capacity determines the capacity of the system as a whole, it is important to identify this critical element.

3.2 Port layout development

3.2.1 Approach

Port layout is an important issue in port development, which should already be addressed in the masterplan phase. It is the visual representation of space allocation to port infrastructure, terminals and port water areas (Figure 3.5). It also reflects the relation of the port to the physical, ecological and socio-economic environment. Together with conceptual designs of the main structures, the port layout provides a good basis for a cost estimate in the feasibility study. Finding a good balance between operational performance and safety, on the one hand, and construction and maintenance costs, is key to port design.

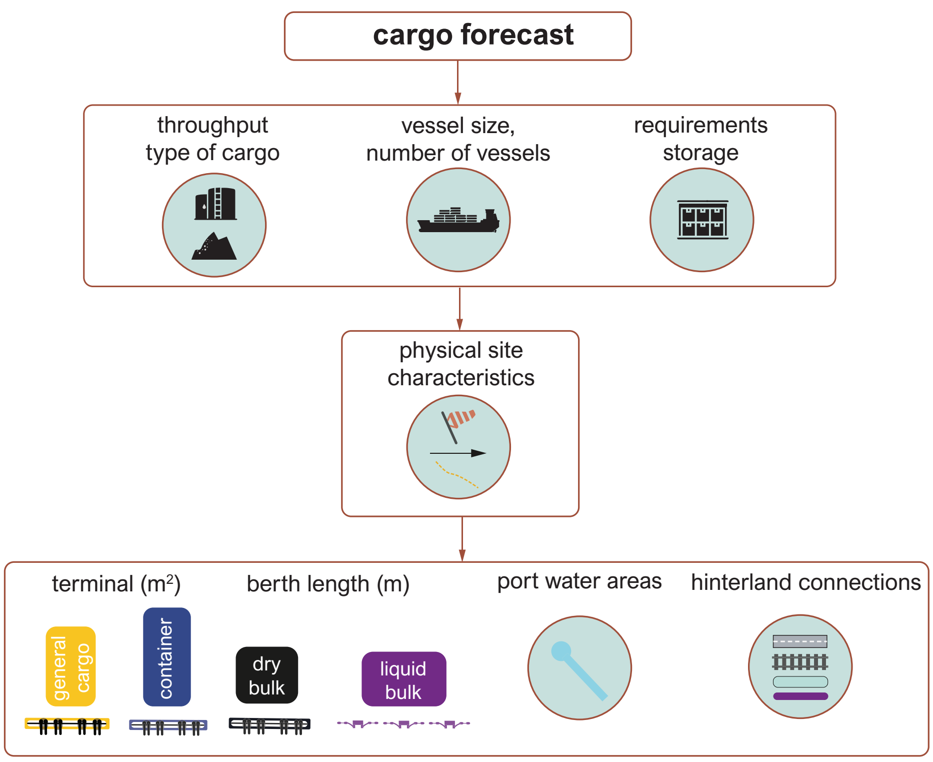


Figure 3.5: Schematic of port layout development (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Once the port has been built, it will be very difficult to change its layout during the operational lifetime (typically 50 to 100 years). Even small layout changes can come with significant costs and may affect the port's operational performance. Yet, there are quite some examples of ports which have been laid out without a proper analysis in the planning stage.

3.2.2 Operational performance

From a logistical perspective excellent operational performance, or port productivity, requires optimal functioning of the complete logistical chain (Figure 3.6).

Figure 3.6: Functional elements of the transport chain (reworked from UNCTAD, 1976, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

A common indicator of port performance is the percentage of uptime, i.e. the time during which vessels can access the port and transfer cargo. The remaining part of the time, called downtime, has two components, viz.:

1. *port access downtime* – which can be caused by:
   - tugs being unable to operate due to high waves,
   - wind, waves or current speeds being too high for access channel passage,
   - fog,
   - ice,
   - blockage of the access channel, due to an accident, maintenance dredging or other,
   - a too low water level, outside the tidal window or otherwise,
   - strikes (tug personnel, pilots, linesmen, etc.).
2. *berth downtime* – which can be due to:
   - wave penetration and/or basin resonance yielding unsafe vessel motions and mooring forces,
   - too high wind speeds for vessel mooring and/or terminal equipment operations,
   - maintenance and repair,
   - strikes (at the terminal).

Table 3.3 presents a calculation of the berth occupancy for a terminal in a situation with little downtime and one with considerable downtime. Berth occupancy for the same operational activity increases when berth availability is less. Note that a high berth occupancy may lead to unacceptably long waiting times. To maintain acceptable waiting times, the berth occupancy in cases of large downtime has to be brought down. This typically goes at the expense of the berth's capacity, the total volume of cargo that can be transferred per year.

	Little downtime	**Large downtime**
Days per year	365	365
Downtime	10 days	65 days
Berth available time	$355 \times 24 = 8520$ hrs	$300 \times 24 = 7200$ hrs
Cargo handling	24 hrs	24 hrs
Other time	1 hrs	1 hrs
Berthing/unberthing	2 hrs	2 hrs
Vessel visits	200	200
Berth time	$200 \times 27 = 5400$ hrs	$200 \times 27 = 5400$ hrs
Berth occupancy	63%	75%

Table 3.3: Downtime-dependence of berth occupancy (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Other factors affecting the operational performance of the port are:

- congestion of the access channel, for instance if it is single-lane,
- lack of available navigational services such as pilots and tugs,
- inefficiency of customs and other procedures,
- not enough cranes, yielding long cargo transfer times,
- inadequate facilities or insufficient capacity for storage,
- insufficient or congested hinterland connections.

When developing a port layout, downtime can be limited by carefully considering:

- *Nautical access (safety)* – orientation of the access channel, such that it enables smooth access and departure; tug and pilot base centred within the port,
- *Wave penetration and basin resonance* – measures limiting wave penetration, and careful basin design to avoid resonance,
- *Breakwater layout* – efficient allocation and layout of port water areas and basins,
- *Berths and terminals* – sufficient berthing length and terminal areas for storage,
- *Port zoning* – sensible zoning to guide port development, and
- *Hinterland connectivity* – good access to hinterland transport of sufficient capacity and punctuality.

In the following sections we further discuss these matters.

3.2.3 Nautical access (safety)

Vessels should experience as little hindrance as possible from currents and waves when entering the port (Figure 3.7). In case of strong waves at the port's entrance, the orientation of the access channel should preferably be in line with the dominant wave direction, in order to have waves from the aft or at most at 15/20°, instead of quartering (45°) or abeam (90°). Abeam wind and currents require higher vessels speeds to keep the vessel on track in the outer access channel. On the other hand, the breakwater layout should limit wave penetration as much as possible, in order to reduce downtime in the port and to provide sufficient shelter for the stopping manoeuvre of the vessel once inside the port. This would require an access channel almost perpendicular to the dominant wave direction. Such a layout would also save construction costs of the breakwater, as it can be built in shallower water. Note that a shore perpendicular access channel would reduce dredging costs, as the channel will reach deep water at the shortest distance. As a compromise between these conflicting requirements, access channels are often built under an angle of about 30° with the dominant wave direction or the shore normal, which gives acceptable manoeuvrability to vessels whilst limiting wave penetration.

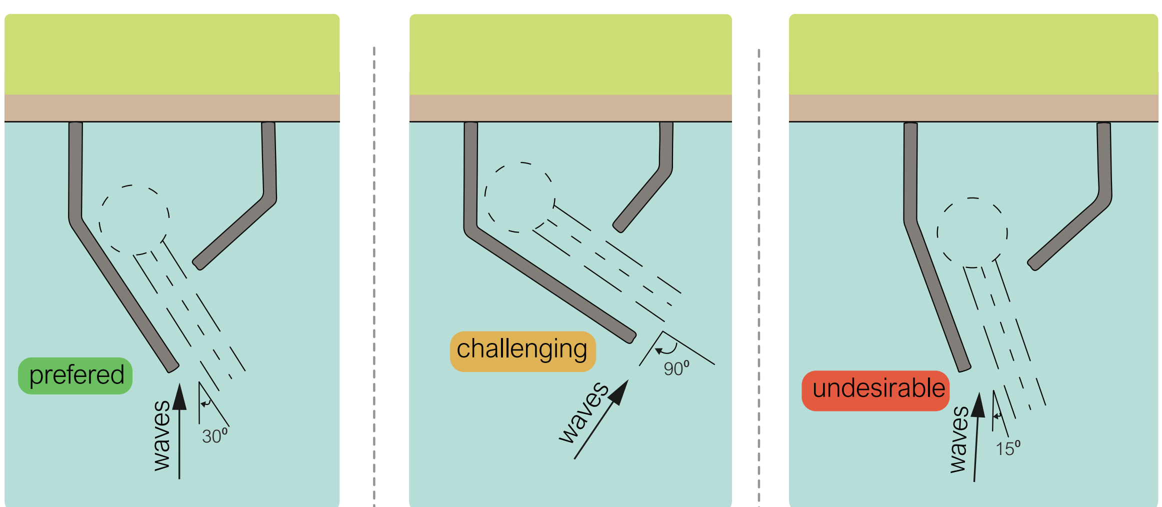


Figure 3.7: Access channel orientation, balancing vessel hindrance and wave penetration (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The best orientation will be selected based on wave penetration and navigation modelling, taking into account local wave and current conditions, whilst optimizing breakwater and dredging costs against operational performance.

Access channels must preferably be straight, avoiding bends in or close to the port entrance, so that vessels don't need to change course in a nautically difficult, sometimes critical area. If local conditions (for instance rocky coastal areas) do not allow for a straight access channel, one may apply very gentle bends, with a radius of at least 5 to 10 time the length of the longest vessel to be expected (Figure 3.8, left). Inside the port, vessels should not make their approach straight into quays or berths, as this may cause accidents should the vessel lose control. If possible, the access channel should be tangential to the area with quays and berths, so that the stopping manoeuvre can be performed with a minimum of risk (Figure 3.8, right).

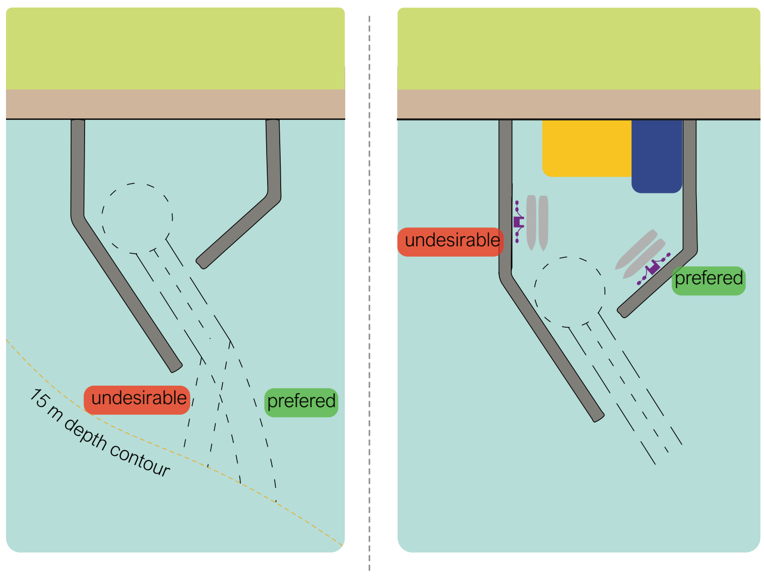


Figure 3.8: Left: curved access channel; right: free stopping range (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Breakwaters should not be too close to the access channel, as the movement of passing vessels may be negatively influenced by the presence of a hard structure. This may lead to collision with the breakwater and blockage of the access channel (Figure 3.9). Moreover, it reduces the flexibility to widen the channel or raise (hence widen) the breakwater. Navigation simulations are often needed to support the design process.

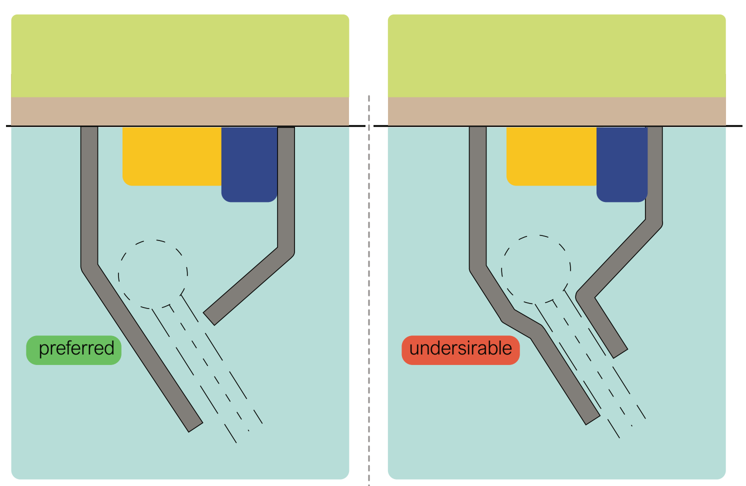


Figure 3.9: Distance of breakwaters to the access channel (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

3.2.4 Wave penetration and basin resonance

Wave penetration and basin resonance should be limited to avoid downtime because of too large vessel motions at berth. Wave penetration is a result of waves propagating into the port through the port access or through diffraction around the tip of the breakwater (Figure 3.10). The left part of this figure also shows that waves can reflect against straight quay walls.

Figure 3.10: Left: wave penetration and diffraction in the Port of Scheveningen, the Netherlands (http: beeldbank.rws.nl, Rijkswaterstaat). Right: Boussinesq model results for Buchanan Port in Liberia to calculate wave penetration around breakwaters (by Royal HaskoningDHV is licensed under CC BY-NC-SA 4.0).

Limiting wave penetration can be achieved by optimising the port layout, in particular by:

- altering the breakwater orientation and layout, especially by
  - increasing the length,
  - changing the orientation with respect to the incoming waves,
  - reducing the width of the entrance, by adding a second breakwater,
- locating the basin such that no wave energy can reflect into it,
- improving the berth layout to avoid exposure to incoming waves,
- limiting reflective structures, or including wave-attenuating elements in the port.

If the frequency of the incident waves equals or approximates one of the eigenfrequencies of the basin, the water body in the basin may start sloshing with a much higher amplitude than the incoming waves. The phenomenon, called basin resonance, may lead to large vessel motions at berth, hence to unsafe situations. Changing the basin size, shape and location, or the layout of the port as a whole, may help reducing this phenomenon. Also wave absorbing slopes and structures may be of use. In the design process, numerical models are often used to investigate this problem.

Table 3.4 gives the limit wave height for safe vessel servicing at a number of terminals (see also Ligteringen, 2017, p. 128). It shows that some cargo operations are more sensitive to waves than others. Therefore, when developing a port layout, one will position the least sensitive operations in areas with the highest wave penetration, and the sensitive ones in more sheltered areas. Operations which allow for higher wave action, such as some liquid bulk jetties, can be located in more exposed areas. In any case, sufficient wave penetration studies should be carried out to avoid unexpected downtime.

Table 3.4 also shows that certain port operations, such as dry bulk and liquid bulk handling, could be carried out in exposed environments without the need of a breakwater, provided that wave conditions remain under a certain limit for most of the time. For bulk operations, which are generally not time-critical and for which there is generally sufficient storage capacity onshore, a certain percentage of downtime may be acceptable, to the extent that they can do without the shelter of a breakwater. On the other hand, container terminals, fishery ports and cruise terminals, which are sensitive to wave action and where the cargo is (very) time-critical, should (almost) always be sheltered by breakwaters.

For further details: see Part III – Section 2.3.

Vessel type	**Limiting wave height H_s in m**	
	0°(head or stern)	**45°– 90°(beam)**
General cargo	1.0	0.8
Container, Ro-Ro	0.5	
Dry bulk (30,000 DWT – 100,000 DWT); loading	1.5	1.0
Dry bulk (30,000 DWT – 100,000 DWT); unloading	1.0	0.8 – 1.0
Tankers 30,000 DWT	1.5	
Tankers 30,000 DWT – 200,000 DWT	1.5 – 2.5	1.0 – 1.2
Tankers > 200,000 DWT	2.5 – 3.0	1.0 – 1.5

Table 3.4: Limit wave height for safe vessel accommodation (d' Angremond and Van Roode, 2004).

3.2.5 Breakwater layout

Breakwaters should prevent wave overtopping under operational conditions. Furthermore, the breakwater and access channel layout should avoid excessive maintenance dredging and limit the morphological impact on the adjacent coastline as much as possible.

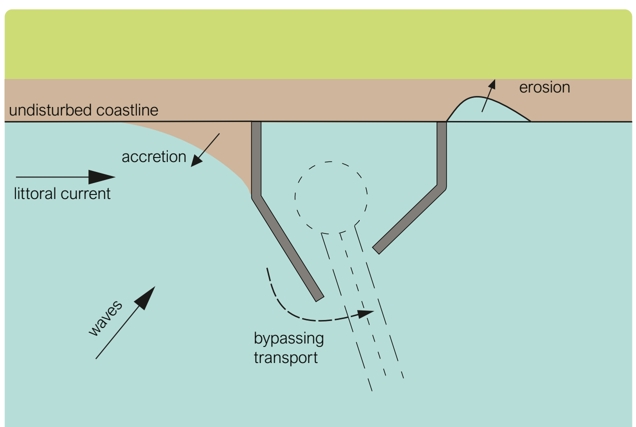


Figure 3.11: Sediment bypassing a breakwater (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The three basic principles for breakwater layout to reduce sedimentation are (also see Ligteringen, 2017):

1. Breakwaters should extend beyond the breaker zone, where the strongest littoral currents occur. As they block the longshore transport, the sediment piles up at the updrift side and the coast erodes at the downdrift side. As long as the updrift coastline has not come so far forward that the sediment transport bypasses the tip of the breakwater (Figure 3.11), sand deposition in the port entrance area is limited. Waves start breaking at a depth of about 1.6 times the wave height. Breakwaters are therefore designed to extend to a depth of 1.6 times the significant wave height exceeded 12 hours per year.
2. If tidal or littoral currents are expected from both sides, a breakwater should be built at each side of the port. Their length differs according to the magnitude and direction of the prevailing sediment transport and the width of the surf zone. Only in situations with waves from one direction, one breakwater will be sufficient.
3. Accretion of sediment over time will push the coastline seaward, hence also the surf zone and the littoral transport. This should be taken into consideration when drafting the breakwater layout, or breakwater

extension will be required over time. An (often expensive and maintenance-intensive) alternative is sediment bypassing, i.e. picking sediment up at the updrift side and pumping it to the downdrift side, thus solving both the updrift accretion and the downdrift erosion problem.

Mitigating measures to limit downdrift erosion should be considered during the port development process. They may encompass beach nourishments, groynes, et cetera.

For further reading see also:

- PIANC (2014a) – PIANC Report N°123 "Coastal Erosion Mitigation Guidelines"

3.2.6 Berths and terminals: rule-of-thumb estimates

Table 3.5 gives an example of a concept design phase calculation of required terminal area and berth length, based on rules of thumb that are usually based on port planners experience (see for instance Ligteringen, 2017, p. 150). These rules of thumb can also be derived by benchmarking against throughput and physical dimensions of existing terminals. More detailed berth productivity and terminal area calculation are covered in Chapter 4 and Chapter 5.

Product		**LNG**	**Containers**	**Dry bulk**
Berth productivity		**8 Mt/(berth · yr)**	**1000 TEU/(m · yr)**	**5 Mt/(berth · yr)**
Gross terminal area		**15,000 t/(ha · yr)**	**20,000 TEU/(ha · yr)**	**20,000 t/(ha · yr)**
		1 month storage		**2 month storage**
Phase 1	Throughput	5 Mt/yr	2 MTEU/yr	10 Mt/yr
	Berth	1 Berth	2000 m	2 Berths
	Terminal*	30 ha	100 ha	100 ha
Phase 2	Throughput	10 Mt/yr	8 MTEU/yr	15 Mt/yr
	Berth	2 Berths	8000 m	3 Berths
	Terminal**	60 ha	400 ha	150 ha

*Table 3.5: Example of rule-of-thumb estimates of terminal and berth dimensions (*rounded to multiples of 10 ha, **rounded to multiples of 50 ha) (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).*

3.2.7 Port zoning

Positioning of berths and terminals, called "zoning", is an important next development step. Zoning can take place at various levels of the planning process:

- *national* – strategy for ports/industrial zones (locations, policy, economy),
- *regional* – relation between port/industrial zone and urban and infrastructural context,
- *local* – clusters within the port/industrial zone with specific characteristics.

For port layout development, local zoning is relevant. Possible considerations are (also see Figure 3.12):

- vessel dimensions and required dimensions of port basins and manoeuvring areas,
- specialised zones for specific commodities,
- safety and environmental aspects:
  - separating dangerous cargoes,
  - minimising collision risks, and
  - locations related to prevailing wind directions,
- hinterland transport: road, rail, IWT and pipeline accessibility, and
- flexibility for terminal extensions and future function changes.

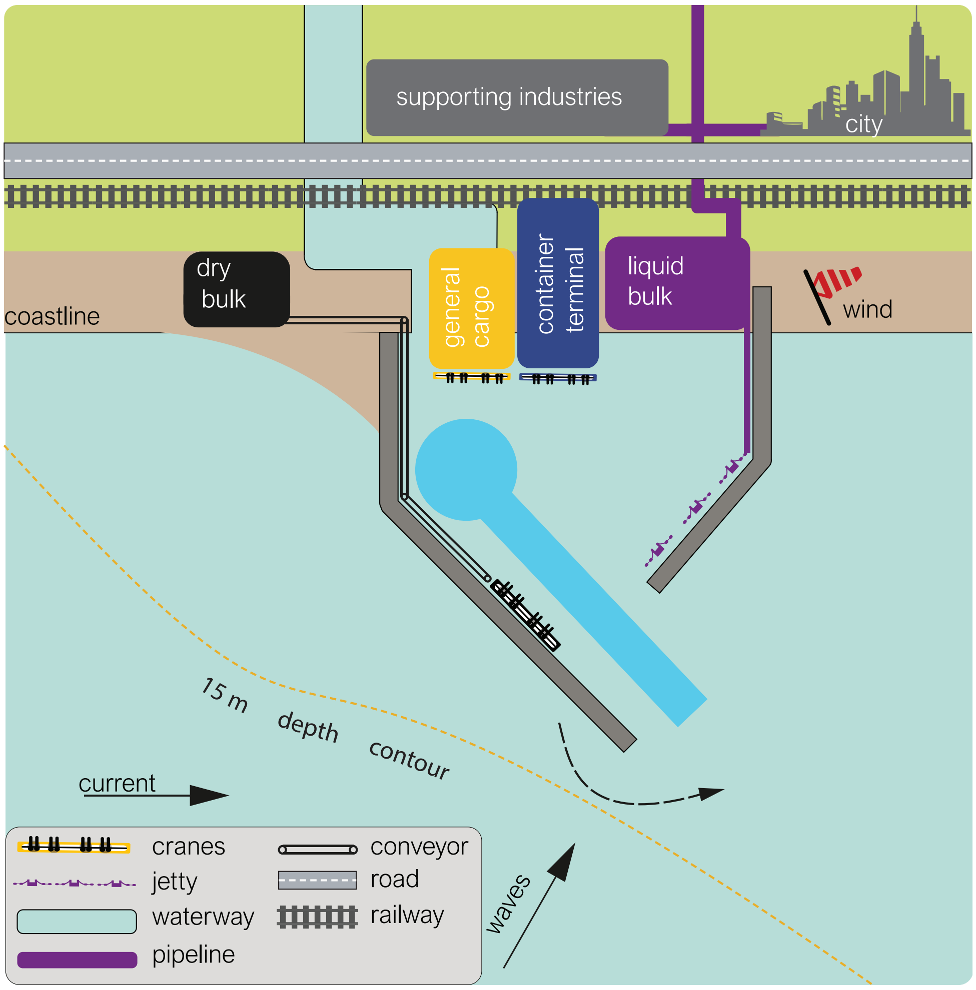


Figure 3.12: Conceptual port layout (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Containers, Ro-Ro vessels and general cargo

Container vessels are often large in size, with a medium draught. They require short turnaround times, straight quays and large terminal areas adjacent to the quay. Moreover, the cargo is usually time-critical, which means that container transport needs excellent hinterland connections via road, rail and IWT.

Ro-Ro vessels are modest in size and draught and require very fast turnaround times, jetties or quays close to the landside port exit and excellent connections with the hinterland.

Container and Ro-Ro cargo handling is very sensitive to wave action, which necessitates locating the terminals on calm waters within the port.

General cargo vessels are often of moderate size and require flexible terminals allowing to handle various goods. Handling general cargo is often less time-critical than containers and RoRo cargo.

Liquid bulk

Vessel sizes can range from very large crude tankers, via medium-draught gas tankers to small-product tankers. Oil, gas and chemical products have strict safety standards, both on water and on land, whence clustering of terminals is often recommended. Especially LPG and LNG have very high safety requirements, and their terminals are often fully separated from other port activities. The passage time of dangerous cargo in access channels should be as short as possible and therefore terminals handling this type of cargo should be located close to the port entrance or even outside the port. In any case, this type of terminal requires a risk assessment and the identification of safety zones.

Terminal type	Berth orientation	Location in the port	Berth to storage / proc.	Near	Away from	Relation to city
Contain-ers	to minimise vessel motion, dredging or reclamation	inner port, calm water	adjacent	road, rail, IWT	airport flight path	outside
General cargo	to minimise vessel motion, dredging or reclamation	inner port, calm water	adjacent	road, rail, IWT	airport flight path	outside
Dry bulk	to minimise vessel motion & dust effects on other terminals	inner or outer port	can be remote, but mind conveyor costs	road, rail, IWT	recreational and public use areas	outside
Liquid bulk	to minimise vessel motion, berting and mooring forces	can be at exposed location, or at SPM	separate (connected via pipeline)	pipelines, tank farms	airport flight path, flammable storage, recreational and public use areas, other berths with exclusion zones	outside
Cars (Ro-Ro)	to minimise tidal effects, berthing and mooring forces	inner port, calm water, connection via ramp	adjacent	road, rail, IWT	dusty port activities	outside
Ferries	to minimise tidal effects, berthing and mooring forces	inner port, calm water, connection via ramp/linkspan	adjacent	road, rail, public transport	dusty port activities	inside
Cruise	to minimise vessel motion (esp. roll), berthing and mooring forces	inner port, calm water, connection via ramp/linkspan	adjacent (if customs and immigration required)	road, rail, public transport, recreation areas, tourist attractions	industrial and dusty activities	inside
Fishing	to minimise tidal and wave effects	inner port, calm water	adjacent	road, rail	dusty port activities	inside
Marinas	to minimise tidal and wave effects, ensure water circulation	inner port, calm water	adjacent	road, commercial water-fronts, prime real estate	industrial and dusty activities	inside

Table 3.6: Port layout requirements for different types of terminals (PIANC, 2019c).

Liquid bulk can be transported by pipeline and hence berths can be positioned away from the other parts of the terminal (see Figure 3.12). Liquid bulk is often loaded and unloaded through hoses or loading arms, which allow for quite some vessel motion. Hence, liquid bulk berths can be relatively exposed.

A good example of a wave-exposed terminal type away from cargo storage is a Single Point Mooring (SPM), which can be located at open sea with a pipeline of several kilometres to onshore storage.

Dry bulk

Dry bulk cargoes are often transported and stored in large volumes, using large vessels with a deep draught. Dry bulk is not time-critical. In view of their dust emission, dry bulk terminals (especially coal) need to be located downwind of sensitive terminals (e.g. containers, shipyards, etc.) and nearby residential areas. Dry bulk can be transported by conveyor belts, so it can be stored away from the quay. The costs involved in the conveyor belt system are actually the limiting factor.

Table 3.6 summarises how these arguments influence the port layout for a number of terminal types and Figure 3.12 gives a conceptual layout in line with this.

3.2.8 Hinterland connectivity

Sometimes a port can thrive as a hub in the worldwide transport network, without much of a hinterland. One example is the port of Singapore, which nevertheless has become one of the world's largest ports. Its unique geographical position, at the crossroads of major trade routes, is a key factor here. In other cases, however, access to a large hinterland with sufficient production and purchasing power is often pivotal to the decision whether or not to further develop an existing port, or where to locate a greenfield port. Good and reliable hinterland connections can reduce logistics costs and transport time, to the benefit of the port's competitive position. In the early planning stages, a port masterplan is therefore integrated in a larger infrastructure development plan, including road, railroad, pipelines, waterways and inland ports. Good and reliable hinterland connections can reduce logistics costs and transport time, to the benefit of the port's position.

3.2.9 Port service areas

In a port layout, the port water areas and terminals require the most space. Yet, quite some other port services need to find a place within the port perimeter. The most common are:

- Tug and support craft base. Apart from tugs, a sizable modern port requires several types of support craft, such as bunker vessels, pilot boats, mooring tenders, crew transfer tenders, oil / chemical spill response, survey / diver support boats, fire fighters (note that modern tugs often also have significant fire-fighting capabilities), and water police. They all need a base inside the port.
- Water supply and water treatment.
- Waste reception facilities (oil, grease, cargo residues, household waste, et cetera).
- Power supply.
- Port Authority and customs.
- Bunkering services.
- Green areas.
- Logistics support industries.
- Ship building / repair facilities.

3.2.10 Cost-reducing measures

The layout determines to a significant extent the investment required to develop a port. Possible cost-reducing choices are:

- Keep the access channels as short as possible, i.e. look – within the range of possible orientations (see Figure 3.7) – for the shortest distance to deep water.
- Locate port water areas as much as possible at water of sufficient existing depth. This reduces capital dredging.
- Reduce access channel dredging by using tidal windows, as far as this acceptable from a waiting time perspective.
- Reduce the breakwater length by applying tidal velocity windows or accepting more weather-related downtime. Clearly, the latter is a trade-off against performance and efficiency, so this will not be an option for busy ports.
- Lay out breakwaters as much as possible in shallow water, because this significantly reduces the volume of costly breakwater material.
- Strive for a cut-fill balance, i.e. the total dredging equals the total landfill volume (Figure 3.13). Major port developments often require significant dredging of port basins and channels. On the other hand, landfill is often needed to bring terrain at the required level and reclamation may be needed to bring the quay line closer to deep water. If the dredged material is suitable for landfill and reclamation, a balance can be found between "cut" and "fill". In environments with coarse sand this is often more feasible than in soft soils, where the dredged material may not be suitable.

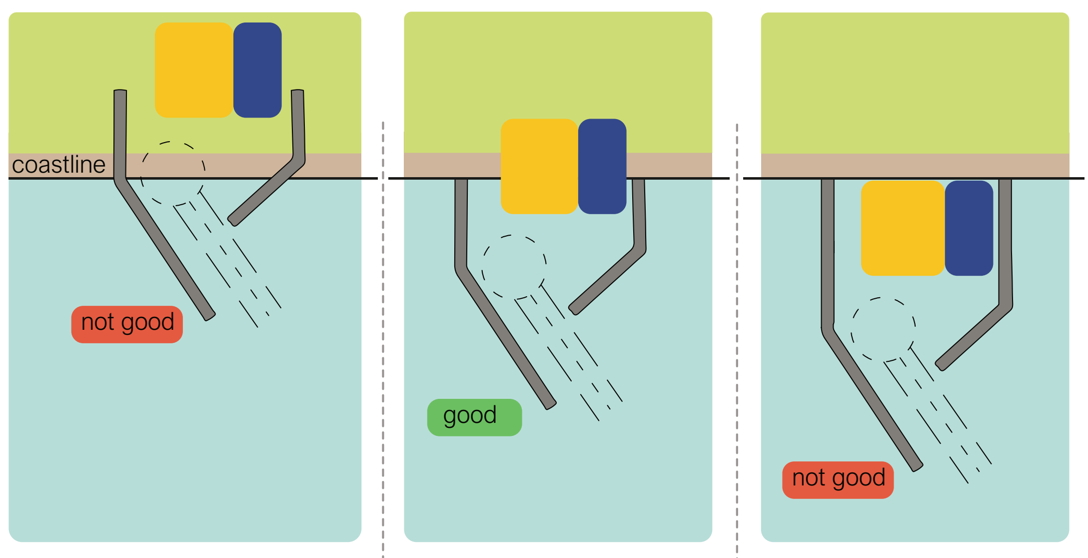


Figure 3.13: Cut-fill balance (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Choices in the layout may also influence the OPerational EXpenditures (OPEX) of a port. Such choices are, for instance:

- to limit maintenance dredging,
- to reduce downtime by optimal orientation of berths with respect to the dominant wind direction,
- to reduce downtime by abating wave penetration,
- to offer vessels easy and safe access and departure, by a proper layout and design of the port water bodies and adequate tug and pilot support.

OPEX over the lifetime of the port generally far exceed the initial investments. For the commercial success of a port, a good balance should be found. Initial CAPital EXpenditures (CAPEX) can be limited as much as possible, but no "pennywise pound foolish" design choices should be made that result in high operational costs and an uncompetitive port later on. Also, one should consider that some CAPEX, such as the costs of a breakwater, are borne by the port authority. Such so-called external costs are not taken into account as CAPEX, at most as OPEX via port fees, in the business case of the terminal. The OPEX resulting from downtime, however, are often paid by the terminal operator. It should further be noted that investments in terminal equipment often exceed the investments in civil engineering port infrastructure.

3.3 Port terminals

While port layout development is at first a qualitative exercise, viz. carefully positioning different port functionalities in the available space, a next step is to develop a more quantitative view of the necessary terminal components (cargo handling equipment on the quay side and land side, as well as storage and processing facilities) and the actual space these require. Different terminal types (i.e. container terminals, coal terminals, liquid bulk terminal etc.) each have specific aspects to consider in terms of required number of terminal elements and their order-of-magnitude dimensions. The combined terminal facilities form the nucleus of the port, to which the water areas and hinterland transport are connected.

3.3.1 Terminal services and components

The services provided at a terminal will differ per commodity, but in general the following facilities are used:

- *mooring facilities* – to allow vessels to safely attach while at the berth,
- *quay side cargo transfer equipment* – in some cases the vessel has onboard gear to offload cargo to the quay, but as vessel sizes increased this became less common.
- *terminal transport equipment* – to distribute cargo from the quay side to the storage areas; this can be conveyor belts for dry bulk, piping for liquid bulk, or vehicles for containers or general cargo,
- *storage facilities* – to allow for a certain dwell time of the cargo and to create a buffer reducing the necessity of direct alignment of cargo entering and leaving the terminal,
- *processing facilities* – bagging of grain, blending of coal, container stripping and stuffing, et cetera,
- *terminal support services* – workshops, terminal buildings, parking, customs et cetera,
- *interfaces to the hinterland* – truck loading facilities, a rail terminal, an IWT terminal, et cetera,
- *gates* – to administer the in- an outgoing transport, and
- *fences* – to secure the terminal.

Table 3.7 gives an overview of typical quayside equipment, storage and supporting facilities and hinterland transport modes for a range of different terminal types. Further details are given in Chapter 4 and Chapter 5.

	Quayside equipment	Storage / onshore facilities	Hinterland
Container	STS cranes	Container stacks	Road, rail, IWT
General cargo	Harbour cranes	Open and closed storage / warehouse	Road, rail
Dry bulk	Ship loaders	Silos, stockyard	IWT, rail, road, conveyor
Liquid bulk	Loading arms, hoses	Tanks, truck loading	Pipeline, IWT, trucks, rail
Ro-Ro	Ramp, linkspan	Parking facilities	Road, train
Fruit	Harbour cranes	Cold storage, refrigerated warehouse. Packaging.	Road
Fishery	Forklifts	Cold storage, refrigerated warehouse. Auction halls, packaging.	Road
Cruise and ferries	Linkspan, walk bridges, catwalk	Passenger terminal building, partling	Road, train
Marinas	Pontoons, walk bridges	Shiplift, winter storage, supplies, parking, etc.	Road

Table 3.7: Facilities per terminal type (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

3.3.2 Terminal capacity

The function of a terminal is to serve as a link in the supply chain, by efficient and fast transfer of cargo, by providing storage facilities and by processing cargo. A terminal's throughput describes the amount of cargo (in tons or TEU) or the number of vessels that it handles over time. A terminal's capacity indicates the maximum throughput it can handle over a given period. In order to be meaningful, however, this quantity requires further specification.

Firstly, it can refer to any operation performed on cargo, be it loading and unloading at the quay, or transport inside the terminal, or processing at the terminal, or loading/unloading at a hinterland terminal, or through-transport to the hinterland, et cetera. But it may also refer to the throughput rate of the whole terminal supply chain (see Part I – Section 2.2.3).

Secondly, capacity has a timescale-attribute. In general, we can distinguish:

- the maximum instantaneous capacity,
- the maximum annual capacity, and
- the optimum annual capacity.

The maximum instantaneous capacity is the maximum amount of cargo per unit time that can be achieved when actually loading or unloading a vessel. It can be only be maintained during a short time, at most the time needed to handle a single vessel. This capacity is of interest to operational managers and to facility and system designers, who have to make sure that this cargo flux can be accommodated in the subsequent operations at the terminal. Otherwise the system will get clogged and overloaded.

The maximum annual capacity is the long-term average capacity that could be attained in case of 100% berth occupation (24/7, 360 days per year), provided that there are no limiting factors landwards of the quay. It is a fictitious quantity, because 100% berth occupation leads to infinite waiting times (see Part IV – Chapter 2), which is absolutely unacceptable to any party involved. Yet, many port authorities use it for publicity reasons, as a measure of the capacity of their port.

The definition of the optimum annual capacity depends on the perspective. From a port-economic perspective, it refers to the cargo throughput that leads to the least overall port costs per unit cargo (tons, TEU or other). For a specific terminal, these overall costs include all fixed and variable costs, all vessel-related costs during service and waiting time, and all port dues. Since these costs are borne by different parties with different economic objectives, it will generally be difficult to achieve this optimum.

Taking the broader economic perspective of the entire supply chain, one may strive for the minimum costs per unit cargo transported from source or supplier to end user. This does not necessarily mean that the costs are minimal for each part of the chain. In practice, such optimisation is only possible if the entire supply chain is centrally managed.

The perspective does not have to be strictly financial, however. Service level, for instance, is an important asset in highly competitive markets. Optimisation by service level means, for example, guaranteeing that the average waiting time of vessels calling at the port will not exceed the average service time by a pre-defined percentage. Queueing theory or simulation models can help find this optimum (see also Part IV).

3.3.3 Terminal dimensions

Important determining factors for the dimensions of a terminal are the quay length and the storage area. They both follow from the envisaged annual mean throughput/storage and the acceptable waiting time. Estimating the required number of terminal elements and assessing their order-of-magnitude dimensions generally involves the steps described below.

Step 1: Cargo forecast

The cargo forecast produces the annual cargo throughput per type of cargo and per terminal. In a large port there can be more than one terminal for the same type of cargo.

In order to be able to design the terminal, we need further information on the cargo flow:

- percentage import,
- percentage export,
- percentage transhipment,
- the peak factor, as defined below, and
- cargo-specific information (e.g. the TEU-factor).

Note that the forecasted cargo throughput is an annual mean. As peak flows can be significantly larger, a port may decide to adjust the cargo handling capacity to a cargo throughput higher than the annual mean. If so, this annual mean has to be multiplied by the peak factor in the calculations for the berth configuration.

Step 2: Fleet composition, cargo distribution

In order to determine terminal dimensions, we have to know how many ships of what class with how much cargo are expected to visit the terminal. This means that for each terminal the cargo flow has to be distributed over the vessel classes to be expected. If the average call size c for each class is known, the average number of vessel calls at the terminal can be estimated.

Table 3.8 shows the principle of this split of cargo flow C (units/year) to a specific terminal. Units can be TEU, tons, passengers, cars, etc.

Vessel class	Vessel mix	Cargo flow	Call size	Nr. calls
I	P_1 %	P_1C	c_1	$P_1C\ /\ c_1$
II	P_2 %	P_2C	c_2	$P_2C\ /\ c_2$
III	P_3 %	P_3C	c_3	$P_3C\ /\ c_3$
Total	100 %	C		$[P_1/c_1 + P_2/c_2 + P_3/c_3]\ C$

Table 3.8: Cargo distribution and number of calls (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Note that 'Nr. calls' has to be a round number, so it will have to be rounded up to the nearest integer value. Multiplying the number of calls with the indicated call size can return a higher value. In further calculations we will therefore use the original throughput C rather than one derived from the number of trips.

Step 3: Cargo specification

The entire throughput C passes over the quay and is divided in import (sea to land), export (land to sea) and transhipment (sea to sea) volumes. The throughput over the terminal amounts to the sum of the import and export volumes plus half the transhipment volume, as transhipment cargo is counted twice in the throughput (coming in and going out), handled twice at the quay, transported twice (from quay to storage and vice versa), but stored only once.

Apart from the throughput, the cargo needs to be specified in terms of quay and transport operations and storage requirements. In the case of containers, for instance, the fractions of laden, empties, reefers and oogs need to be known, because these require different storage conditions (area, facilities). In the case of cars it may be batches of different brands for different storage yards / distributors. This cargo split will be different for the quay throughput and the storage yards, due to the transhipment effect mentioned above.

Step 4: Berth configuration

The berth configuration depends on a number of properties of the vessels, viz.:

- mooring time,

- unmooring time,
- length overall L_{OA},
- beam B_s,
- draught D_s,

for each vessel class.

In addition, we need information on the cargo handling equipment, like:

- type of (un)loading facility (e.g. Ship-To-Shore (STS) crane, conveyor belt, pipeline),
- handling capacity (e.g. TEU or boxes/lift, ton/lift, m^3/hour),
- number of cycles per hour (e.g. lifts/hour),
- number of operational hours per year,
- efficiency factor,
- number of facility units per quay,
- type of facilities for transport to/from the storage yard (e.g. tractor trailers),
- number of transport units per (un)loading facility unit (e.g. tractors per crane).

Step 4.1. Number of berths, quays and unloading equipment needed

Let us take the approach that the average waiting time in units of average service time is the determining factor for the number of berths, quays and (un)loading facility units. For every cargo/terminal type there is an upper limit to this ratio (see PIANC, 2014b):

- bulk terminals: 0.3,
- general cargo terminals: 0.2,
- container terminals: 0.1.

The ratio for container terminals is the smallest, because container vessels often operate in tightly scheduled round-trips, so delays in consecutive ports would accumulate. Moreover, on-time delivery claims put pressure on the shipping lines to avoid delays. This is less so for bulk cargo.

Berth occupancy	**Number of berths n**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
30 %	0.32	0.08	0.03	0.01	0.00	0.00	0.00	0.00
40 %	0.50	0.15	0.06	0.03	0.02	0.01	0.01	0.00
50 %	0.75	0.26	0.12	0.07	0.04	0.03	0.02	0.01
60 %	1.13	0.43	0.23	0.14	0.09	0.06	0.05	0.03
70 %	1.75	0.73	0.42	0.27	0.19	0.14	0.11	0.09
80 %	3.00	1.34	0.82	0.57	0.42	0.33	0.27	0.22
90 %	6.75	3.14	2.01	1.45	1.12	0.91	0.76	0.65

Table 3.9: Waiting time to service time ratios for the M/E2/n-pattern (source: Groenveld, 2001).

Berth occupancy	**Number of berths n**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
30 %	0.13	0.02	0.01	0.00	0.00	0.00	0.00	0.00
40 %	0.24	0.06	0.02	0.01	0.00	0.00	0.00	0.00
50 %	0.39	0.12	0.05	0.05	0.01	0.01	0.01	0.00
60 %	0.63	0.22	0.11	0.06	0.04	0.03	0.02	0.01
70 %	1.04	0.41	0.23	0.14	0.10	0.07	0.05	0.04
80 %	1.87	0.83	0.46	0.33	0.23	0.19	0.14	0.12
90 %	4.36	2.00	1.20	0.92	0.65	0.57	0.44	0.40

Table 3.10: Waiting time to service time ratios for the E2/E2/n-pattern (source: Groenveld, 2001).

Queueing theory establishes the relationship between waiting time and berth occupancy, given the number of berths. Table 3.9 gives an example, assuming random vessel arrivals with an exponential (Markov) probability distribution and an Erlang-2 distribution of service times. Note that these are conservative estimates, because vessel arrivals are seldom completely random. A more realistic arrival pattern, at least for specialist bulk terminals, is the Erlang-2 distribution. Table 3.10 gives the waiting time to service time ratios for that case.

The difference between Table 3.9 and Table 3.10 shows how much the number of berths depends on the assumed arrival distribution. For container vessels arrivals are even less random, so there the ratios are still smaller.

Tables like these are useful for first estimates in the early design phases. At later stages of the design process, one needs more accurate results, such as upper and lower bounds of the waiting time to service time ratio. They follow from more refined queueing tables or simulation modelling (see also Part IV – Chapter 2).

With 'waiting time to service time ratio' tables we can make a first estimate of the required number of berths, quays and (un)loading units by systematically increasing them one by one, until the maximum acceptable waiting time to service time ratio is achieved. Table 3.11 gives an example for a fictitious container terminal, using linear interpolation between the data in Table 3.9. It uses the following basic data:

- number of operational hours per year: 8,500,
- total unloading time (all cranes together): 20,000 hours per year,
- total (un)mooring time (all vessels together): 1,500 hours per year,
- maximum number of berths per quay section: 1, and
- maximum number of cranes per quay section: 4.

Itera-tion	**Action**	**Configuration**			**(Un)moor-ing**	**(Un)loading time**	**Occu-pancy (%)**	**WT/ST**
		berths	**quays**	**cranes**				–
0	greenfield	0	0	0	–	–	–	–
1	add berth	1	0	0	–	–	–	–
2	add quay	1	1	0	–	–	–	–
3	add crane	1	1	1	1.500	20.000	253	> 4.36
4	add crane	1	1	2	1.500	10.000	135	> 4.36
5	add crane	1	1	3	1.500	6.666	96	> 4.36
6	add crane	1	1	4	1.500	5.000	76	2.14
7	add berth	2	1	4	1.500	5.000	76	2.14
8	add quay	2	2	4	1.500	5.000	76	2.14
9	add crane	2	2	5	1.500	4.000	65	0.32
10	add crane	2	2	6	1.500	3.333	57	0.19
11	add crane	2	2	7	1.500	2.857	51	0.13
12	**add crane**	**2**	**2**	**8**	**1.500**	**2.500**	**48**	**0.09**

Table 3.11: Procedure to determine the required configuration of berths, quay sections and cranes (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The occupancy follows from:

$$\text{occupancy} = (\text{unloading time per crane} + \text{(un)mooring time})\,/\text{number of operational hours} \tag{3.2}$$

Given the occupancy and the number of berths, the waiting time to service time ratio (WT/ST) follows from Table 3.9 by interpolation. Here we use a cut-off value of WT/ST of 0.1, which would correspond with a container terminal (PIANC, 2014d). For other terminal types other cut-off values may apply, yielding other numbers of berths and cranes. The configuration required to achieve the cut-off value of 0.1, in this example is a combination 2 berths, 2 quay sections and 8 cranes.

Step 4.2. Quay or jetty

The choice between a quay and a jetty is often determined by the type of cargo. Liquid bulk terminals, for instance, don't need heavy cranes and road or rail transport to the terminal. Then a jetty can be a cheaper solution than a quay.

If the type of terminal requires one or more quays, the vessel size and the dock layout are important determining factors for the quay length (see Table 3.2). Assuming the dock layout to be linear, Table 3.2 gives distances between berths between 10 and 30 m, depending on the vessel length. We assume here a berthing gap of 15 m. Moreover, at each end of a linear quay structure there has to be a free space, which we also take 15 m. For a quay structure with a single berth, this means that its length follows from ((UNCTAD, 1985)):

$$L_q = L_{s,max} + 30\text{m} \tag{3.3}$$

For a quay structure with n berths UNCTAD (1985); **?** suggests:

$$L_q = 1.1n\,(L_{s,av} + 15) + 15\text{m} \tag{3.4}$$

The factor 1.1 compensates for the variation around the average.

One may reserve at least one berth for the largest vessels, so that the minimum total quay length for n berths follows from

$$L_q = L_{s,max} + 1.1\,(n-1)\,(L_{s,av} + 15) + 30\text{m} \tag{3.5}$$

Step 4.3. Quaywall retaining height and sheetpile length

For the design of the quay structure the water depth at the berth needs to be known. It follows from

$$h_q = \text{draught} + \text{maximum sinkage} + \text{wave-motion} + \text{UKC} \tag{3.6}$$

The height of the quay with respect to the berth bottom is equal to h_q plus the freeboard.

If the quay platform is built on an earth-retaining quaywall in soft soil, a rule of thumb for the required length of anchored sheetpiles as quaywall is twice this retaining height.

Step 4.4. Apron surface area

The width of the apron depends on the type of cargo. The apron width should be sufficient to accommodate the mooring facilities, the unloading cranes, and roads connections to the rest of the terminal. The apron surface area is simply equal to the total quay length (Equation 3.5) times the apron width.

Step 5. Quay to storage transport equipment

This, again, depends on the type of cargo. Firstly, we need to specify the equipment (type, quantity) for transport between quay and stack. In order to prevent congestion, the total transport capacity has to be in line with the (un)loading capacity at the quay. Moreover, synchronisation can be a point of attention, for instance in the case of STS-cranes. Whenever a crane is ready to deposit an unloaded batch, a means of transport has to be ready to pick it up and bring it to the stack (or vice versa). In practice it means that the number of transport equipment is proportional to the number of cranes.

Another important choice is the equipment at the storage yard (in the case of containers: type of gantry cranes, carrying equipment, empty handlers, etc.). This determines the required storage area, as well as the efficiency of the storage operation at the terminal.

Step 6. Storage area

The basis of the storage area computation is the net area needed to store the throughput (corrected for transhipment and multiplied by the peak factor) during a certain amount of time, the dwell time. As the dwell time is usually expressed in days, the throughput has to be expressed in volume or units per day. Note that ground space requirements and dwell time are not necessarily the same for every type of cargo stored. In the case of containers, for instance, they will vary between loaded containers, empties, reefers and Out Of Gauges (OOGs).Apart from the net area, there has to be room for transport (roads, rails, manoeuvring space).

A crude first-order calculation method is to divide the corrected throughput by a capacity factor, which varies between types of cargo. Table 3.12 gives rule-of-thumb values of capacity factors (taking room for rails, roads, etc. into account), as summarised by Ligteringen (2017).

Cargo type	Capacity factor	Units
conventional general cargo	4 – 6	t/yr per m^2
containers	0.75 – 5.5	TEU/yr per m^2
coal – import	15 – 75	t/yr per m^2
iron ore – import	30 – 80	t/yr per m^2
crude oil	40 – 50	t/yr per m^2

Table 3.12: Indicative capacity factors for storage area estimation (Ligteringen, 2017).

Note that this approach is only suitable for order-of-magnitude estimates. In the next chapter we will show a more elaborate example of a storage area calculation for a container yard.

Step 7: Storage to hinterland transport

A terminal is an enclosed space where the amount of stored goods is controlled. So if goods leave the terminal for transport to the hinterland, or vice versa, this has to be registered. Furthermore, international transport requires customs formalities. The places where this all happens are the gate for road transport, the railway terminal for rail transport and the IWT-terminal for waterborne transport. Facilities and procedures need to be designed such, that they don't form a bottleneck in the cargo throughflow.

Taking the gate as an example, we first need to know the cargo flows by road into and out of the terminal. Subsequently, these are translated into annual mean truck moves in and out. This number may be corrected for empty trucks entering or leaving the terminal, because they need no inspection of their cargo. As truck moves vary over time, we multiply the annual mean number of moves by a gate peak factor (gpf), which consists of three components:

$$gpf = pf_{week} \cdot pf_{day} \cdot pf_{hour} \tag{3.7}$$

for the busiest week in the year, the peak day in the peak week, and the peak hour on the peak day, respectively. The design gate capacity is a (high) percentage of the number of truck moves per hour times the gate peak factor. Finally, the operational time fraction of a single gate needs to be known (say 1, i.e. 60 min/hour) and the time needed for entry- and exit-inspections of an individual truck load, respectively.

Given this information, we can work out the number of inspection minutes (entry and exit separately) per hour the gate system has to be designed for:

$$t_{g,exit} = \text{truck moves out per hour} \times \text{exit inspection time} \tag{3.8}$$

$$t_{g,entry} = \text{truck moves in per hour} \times \text{entry inspection time} \tag{3.9}$$

The number of exit gates needed is then the next higher integer of $t_{g,exit}/(60 * \text{operational time fraction})$ and the number of entry gates that of $t_{g,entry}/(60 * \text{operational time fraction})$.

Step 8. General services

On top of the apron and storage areas, space is needed for facilities like a general office, a workshop, a general repair building, parking space for terminal transport equipment, parking for trucks, a place for scanning and inspection, railway terminal, etc.

Step 9. Summary

As a ninth step we generally summarize the results of the first-order design efforts.

In Chapter 4 we consider container transport and terminals in more detail and elaborate an example application of these steps. Chapter 5 addresses other terminal types and what is important to consider in their design. For more information the reader is referred to “Ports and Terminals” by Ligteringen (2017).