Part I - Ch 1 Ports and waterways systems

van Koningsveld, M.; Verheij, H.J.; de Vriend, H.J.

Publication date
2021

Document Version
Final published version

Published in
Ports and Waterways

Citation (APA)
van Koningsveld, M., Verheij, H. J., & de Vriend, H. J. (2021). Part I - Ch 1 Ports and waterways systems. In M. V. Koningsveld, H. J. Verheij, P. Taneja, & H. J. de Vriend (Eds.), *Ports and Waterways: Navigating a changing world* (pp. 5-23). TU Delft OPEN Publishing.

1 Ports and waterways systems

Ports and waterways are parts of a coherent system enabling supply chains over water. Their functions, design, operation and maintenance influence the performance of these supply chains and the transport system as a whole. This chapter gives a general orientation, terminology and essential definitions, as well as an introduction into how the elements of the transport system interact.

1.1 On the importance of waterborne transport and its facilities

Maritime trade dates back to prehistoric times. The first maritime trade routes are attributed to the Austronesian people, around 1500 BC, who, living in a region with over 20.000 small and larger islands, had been seafarers for thousands of years. The Austronesian trade network expanded as far as East Africa, the Arabian Peninsula, South Asia, South-East Asia and China (Figure 1.1). It facilitated the spread of South-East Asian spices and Chinese goods to the west, as well as the spread of Hinduism and Buddhism to the east. This led to what would later become known as the Maritime Silk Road (see also Wikipedia: Trade_route).

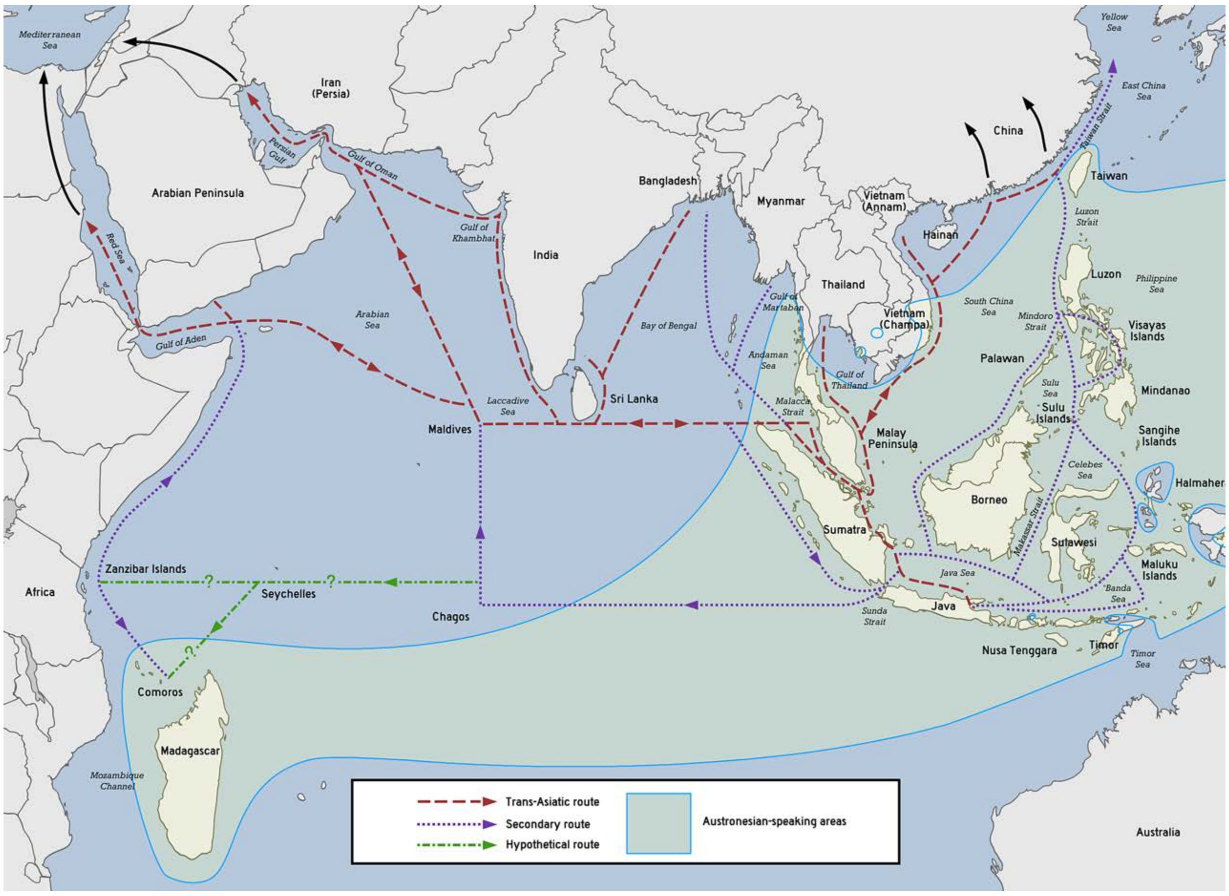

Figure 1.1: Austronesian maritime trade network in the Indian Ocean (by O. Soul is licenced under CC0 1.0).

Later on, in Greco-Persian and Greco-Roman times, extensive maritime trade networks developed in the Mediterranean and, after the annexation of Egypt, with India via the Red Sea. Further north, the Hanseatic network between North Sea, Sont and Baltic ports gained importance after about 1200 AD. During the 'Age of discovery', starting in the 15th century, profitable spice trade gradually became an important driver of long-distance maritime transport. Worldwide trade took off after the discovery of the Americas and led to a dense present-day network of waterborne trading routes (Figure 1.2).

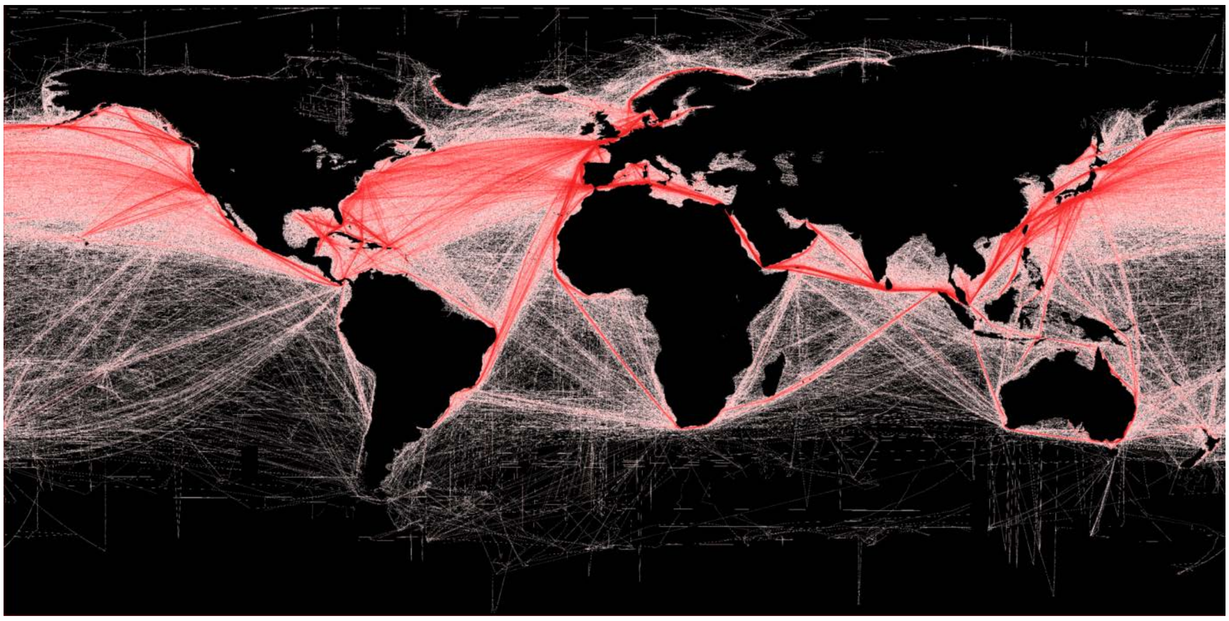

Figure 1.2: Present-day commercial shipping routes (by B.S. Halpern (T. Hengl; D. Groll) is licenced under CC BY-SA 3.0).

Not only the shipping route network has globalised and intensified dramatically, also the amounts of transported goods. Substantial maritime trade, in terms of volume and value, was already possible for centuries, albeit often powered by muscle, wind and sail. Since the early 1800s, the advent of steam technology helped to drastically boost the transport capacity of roads, railways and pipelines, as well as of overseas and inland waterborne transport. As a consequence, nowadays multiple modes of transport are available to transport massive amounts of cargo.

Waterborne transport systems cannot operate without ports. They provide transfer capacity to connect different transport routes (and transport modes) making it possible to bring goods to their final destination. Ports also provide storage facilities needed to match the transport capacities of the network branches they connect, and space for industries to add value to the transported goods. Ports have many functions, as trading centres and centres of industrial activity, but also as centres of exchange between cultures, since ships bring not only goods, but also people. This explains why port regions have always been attractive for settlement. Furthermore, ports themselves are strategically important: many political conflicts have been driven by the access to ports.

Another important element in waterborne transport systems are waterways. They can be natural waters, such as oceans, seas, estuaries, rivers and lakes, but many of these have been modified or built by man. Some of these man-made waterways have had effects worldwide: the Suez Canal shortened the distance between Europe and South-East Asia and boosted connections between these continents; the Panama Canal gave a major impulse to trade between the Atlantic and Pacific Ocean basins. Others are of regional importance, but nonetheless economically crucial: what would the Port of Rotterdam be without the inland waterway to the German Ruhrgebiet and further into Europe?

Ports and waterways are not just elements in a logistic network, they are also major engineering objects. Thus civil engineering is key to ports and waterways, but ports and waterways are also a major issue in civil engineering. Broader than just civil engineering, however, port and waterway planning is a multi-disciplinary activity by nature. It involves expertise in the field of transport-economics, shipping, nautical matters, safety and logistics. It also requires knowledge of waves and currents, sediment transport and coastal and riverine morphology, dredging and land reclamation, and design of breakwaters, quays and jetties. Thus, effective port and waterway planning requires teamwork.

Port and waterway infrastructures, such as access channels, breakwaters, quay walls and locks, involve major investments and take a long time to develop. They are built for decades ahead, so a future-proof design based on a strategic view on maritime and inland transport, as well as on current and future operating conditions and restrictions, is crucial to their success. Failure means that transport and trade move over to other ports, with economic decline as a consequence.

1.2 Terminology and definitions

To create common ground for the further discussions in this book, this section introduces some general terminology and definitions related to waterborne transport networks and supply chains. More detailed definitions will be provided throughout the book wherever appropriate.

1.2.1 The transport network and its elements

A waterborne transport network consists of nodes (ports with their facilities), connected by edges (shipping routes and inland waterways). The total transport network may also involve infrastructure for alternative transport modes, like airports, roads, railroads and pipelines. Civil engineering infrastructures, like access channels, breakwaters, quay walls, inland waterways, bridges and locks, influence the transport capacity that a water network may achieve (Figure 1.3). This transport capacity is an important performance criterion for waterborne supply chains.

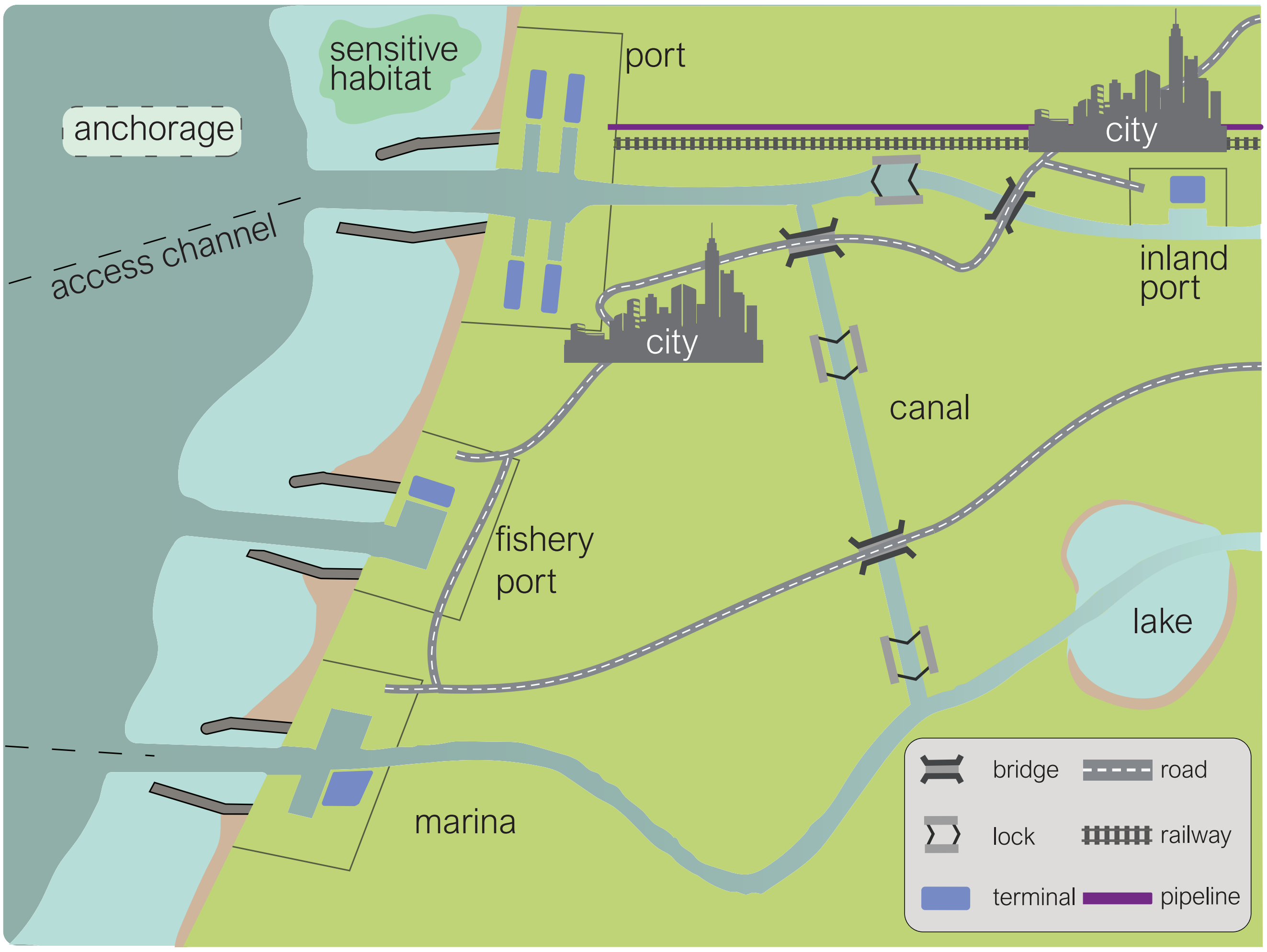

Figure 1.3: Elements of a transport network (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Supply chain

The combination of activities and facilities involved in moving a product or good from supplier to customer is called the supply chain. Supply chain analyses typically extend from the sourcing of raw materials and intermediate products, via the assembly into final products, up to delivery to the customer. As such, supply chain analyses give insight into what the products are made of, where they come from, where they go, and how and via what route they are transported. The transport aspects of supply chains are of particular interest to port and waterway engineers (Figure 1.4).

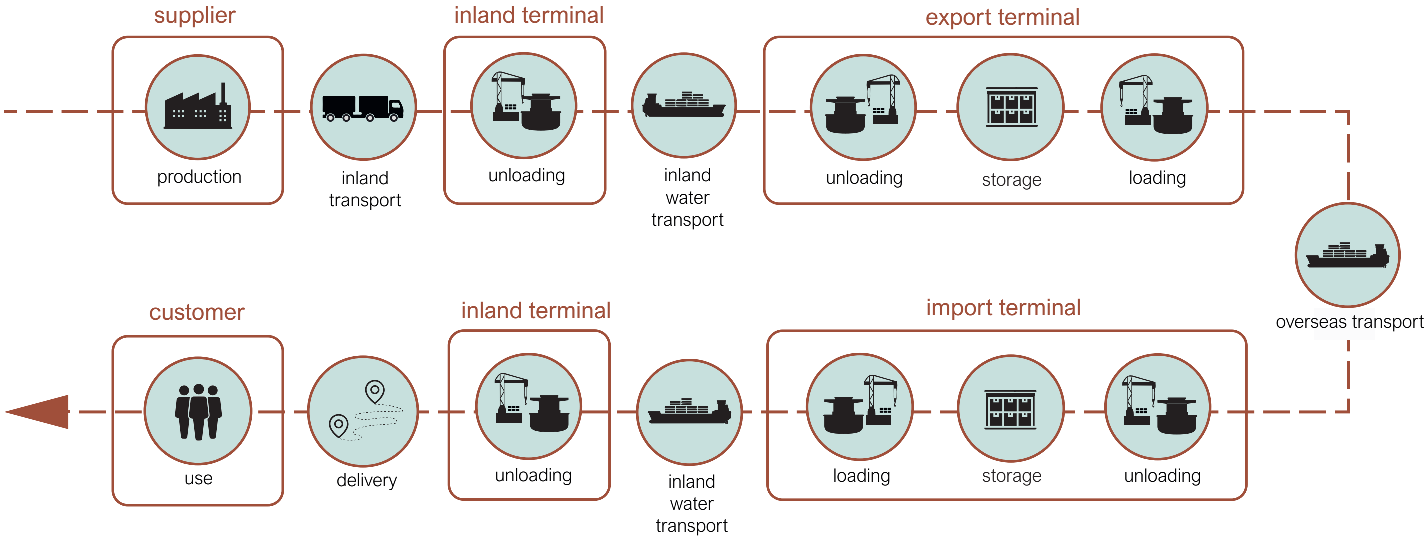

Figure 1.4: Schematics of an overseas supply chain (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Port

The term port is often used to refer to a complex of infrastructures that facilitates vessels to (un)load their cargo, and cargo to be transferred from one mode of transport to another. A port complex may contain various cargo-specific terminals (Figure 1.5), including facilities for handling and storage of cargo. Apart from cargo-specific terminals, a port complex generally includes facilities for bunkering (fuel supply to ships), repair, customs, etc.

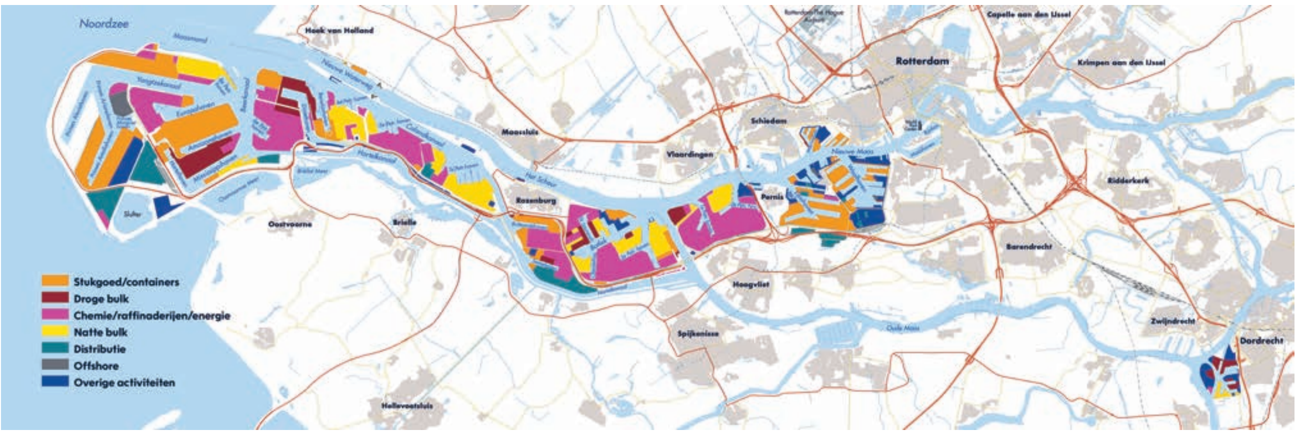

Figure 1.5: Overview of the Port of Rotterdam (by Port of Rotterdam is licenced under CC BY-NC-SA 4.0).

Many ports are cargo-specific, which enables them to optimise their infrastructure for handling this specific type of cargo (Figure 1.6, left). The same goes, of course, for passenger, ferry and cruise ports (Figure 1.6, right). For inland ports this situation occurs at industrial ports serving a single factory. The hinterland of a port refers to the area that a port serves, both for imports and for exports. Part of a ports hinterland may be situated in neighbouring countries.

Figure 1.6: Left: Petrolesport JSC Ro-Ro terminal in St. Petersburg, Russia (by Pavel Iovik is licenced under CC BY-SA 4.0); Right: Bornholm ferry terminal in Rønne, Denmark (by pxhere.com is licenced under CC0 1.0).

Marine shipping route

In seas with high navigation densities, such as the North Sea, there may be designated shipping lanes for traffic regulation (Figure 1.7), but in the open ocean there are none. Marine shipping routes are therefore defined by the ports they connect or by their position on the globe.

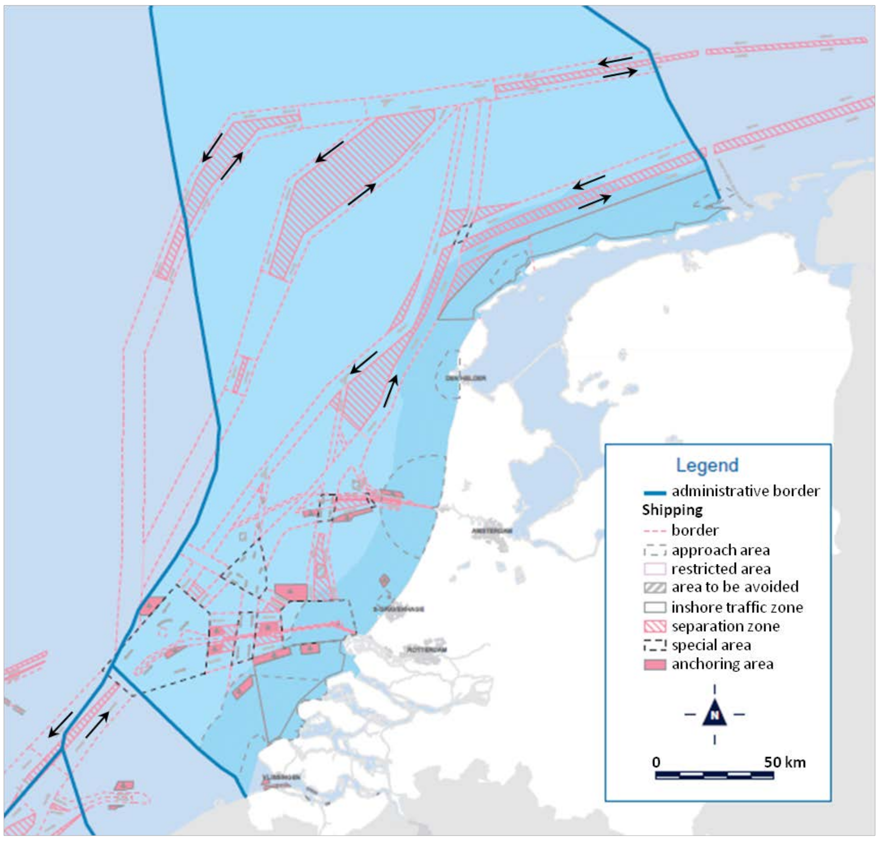

Figure 1.7: North Sea shipping lanes (by Noordzeeloket is licenced under CC0 1.0).

Waterway

A waterway is a water body, usually inland, that enables waterborne transport of goods and passengers. A waterway can be open or closed, depending on whether it is segmented by hydraulic structures such as weirs and locks. The River Waal (Figure 1.8, left) is an example of an open waterway, the River Maas (Meuse) upstream of Lith is a closed waterway in times of low discharges (Figure 1.8, right). Note that inland waterways may have multiple functions (discharge of water, sediment and ice, water supply, cooling capacity, fisheries, ecosystem support, recreation, etc.).

Figure 1.8: Left: the Waal, an open waterway (https://beeldbank.rws.nl, Rijkswaterstaat); right: the Maas at Lith, a closed waterway (https://beeldbank.rws.nl, Rijkswaterstaat, by: Joop van Houdt).

In a transport context, waterways are often distinguished by class. These classes are based on horizontal dimensions, particularly the width of vessels, but (air) draught plays a role. In Europe the CEMT-1992 classes are in use (CEMT, 1992). In the Netherlands extra classes are added for coupled vessels (RVW, 2020). An international overview of design guidelines for inland waterways is published by PIANC (2019a).

Transport mode

Waterborne transport modes are:

- ocean shipping (intercontinental, long distance, large volumes; Figure 1.9, left),
- short sea shipping (coastal, shorter distance, smaller volumes; Figure 1.9, right),
- inland shipping,
- passenger transport, and
- recreational navigation.

Furthermore, there is transport by air, road, rail and pipeline, which enables modal shift.

Figure 1.9: Left: Ocean shipping (CSCL Atlantic Ocean by Alf van Beem is licenced under CC0 1.0); Right: Short sea shipping (Shortsea-Containership-by-Hessel-Visser-2012 by Seuteraar is licenced under CC BY-SA 3.0).

1.2.2 Infrastructure

Port infrastructure

Every port has its specific properties, but they all have in common that they are a link in one or more waterborne supply chains and an interface between transport modes. To that end, every port comprises a number of essential facilities (also see Figure 1.10, for the example of a container port):

1. the wet infrastructure:
    - approach channel(s),
    - manoeuvring areas,
    - mooring basins,
    - anchorage areas,
2. aids to enable a ship to make a safe landfall:
    - pilot system,
    - tug support system,
    - linesmen and stevedores,
3. dry infrastructure:
    - terminals for passenger and cargo handling,
    - storage facilities,
    - connecting transport systems.

Figure 1.10: Container port facilities Rotterdam (Digitalisering Haven Rotterdam by Havenbedrijf Rotterdam N.V. is licensed under CC BY-NC-SA 4.0).

Harbour

A harbour is a natural or man-made physical space that provides shelter and mooring facilities to vessels. So a port in a waterborne transport network includes one or more harbours (Figure 1.11, left), but a harbour is not necessarily a port or part of a port. Examples are overnight harbours (Figure 1.11, right) and refuge harbours, which have no loading and unloading facilities for cargo or passengers.

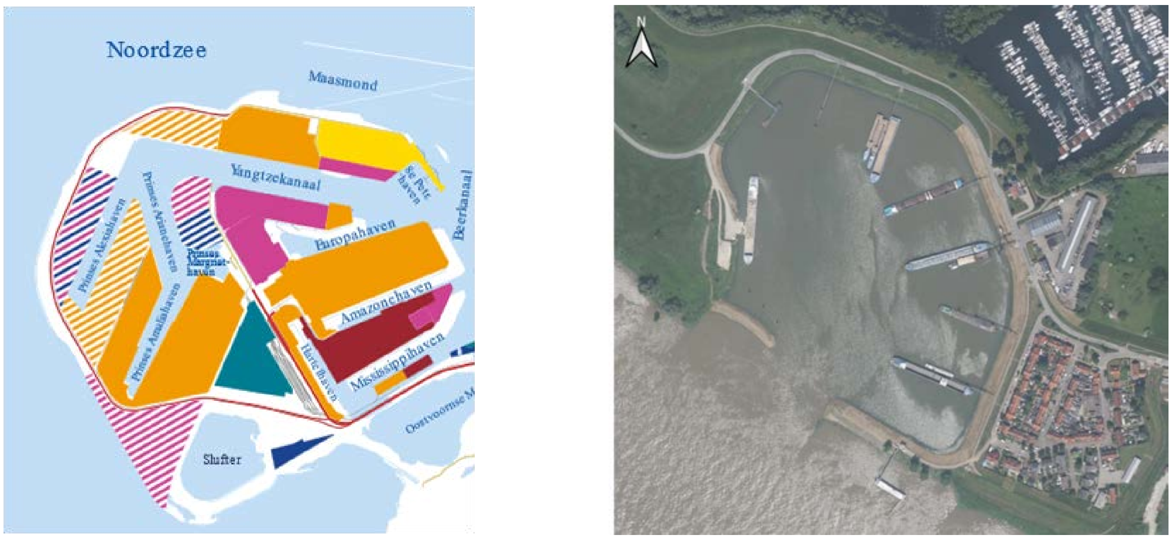

Figure 1.11: Left: The harbours of the Maasvlakte, Port of Rotterdam (RotterdamPort by Vorpzn is licenced under CC0 1.0); right: Overnight harbour Lobith (aerial imagery by the National Georegister (NGR) is licenced under CC BY 4.0).

Terminal

A terminal is a man-made structure that facilitates the transfer of passengers or one or more specific types of cargo from one mode of transport to another, such as a container terminal (Figure 1.12, left). Note that terminals can also be located outside the actual port area, e.g. for handling hazardous goods such as Liquified Natural Gas (LNG) or hydrogen (Figure 1.12, right).

Figure 1.12: Left: Container terminal (by pxhere.com is licenced under CC0 1.0); right: LNG-terminal (by Jan Arrhénborg / AGA is licenced under CC BY-SA 3.0).

Other types of terminals are:

- ferry terminals (Figure 1.6, right),
- liquid bulk terminals, e.g. for crude oil or chemical products (Figure 1.13, left),
- dry bulk terminals, e.g. for coal or ore (Figure 1.13, right),
- roll-on roll-off (Ro-Ro) terminals, e.g. for cars (Figure 1.14, left),
- cruise terminals (Figure 1.14, right),
- river barge terminals (Figure 1.15, left),
- fisheries terminals (Figure 1.15, right).

Figure 1.13: Left: Liquid bulk chemicals terminal, Rotterdam (by Royal HaskoningDHV is licenced under CC BY-NC-SA 4.0); right: dry bulk terminal, Rotterdam (PIANC, 2019b).

Figure 1.14: Left: Ro-Ro terminal (Navio do tipo ro-ro by J. A. Moreira & M. Vivaldini is licenced under CC BY 4.0); right: cruise terminal, Sand Diego, USA (Cruise Ships Visit Port of San Diego by Port of San Diego is licenced under CC BY 2.0).

Figure 1.15: Left: River barge terminal (image by pxhere.com is licenced under CC0 1.0); right: Fisheries terminal, Scheveningen (Scheveningen Haven by harry_nl is licenced under CC BY-NC-SA 2.0).

Access channel

Ports are not always directly located on deep water. Access channels are meant to give deep-draught vessels access to ports on shallow water or at some distance inland. An old example is the Nieuwe Waterweg, which was built in 1872 and connects Rotterdam with the North Sea. Later on, larger vessels required extending it by dredging an access channel through the shallow coastal area, the Euro-Maas Channel (Figure 1.16, left). A more recent example is the Deep Water Navigation Channel in the Yangtze Estuary, giving deep-draught vessels access to the port of Shanghai (Figure 1.16, right).

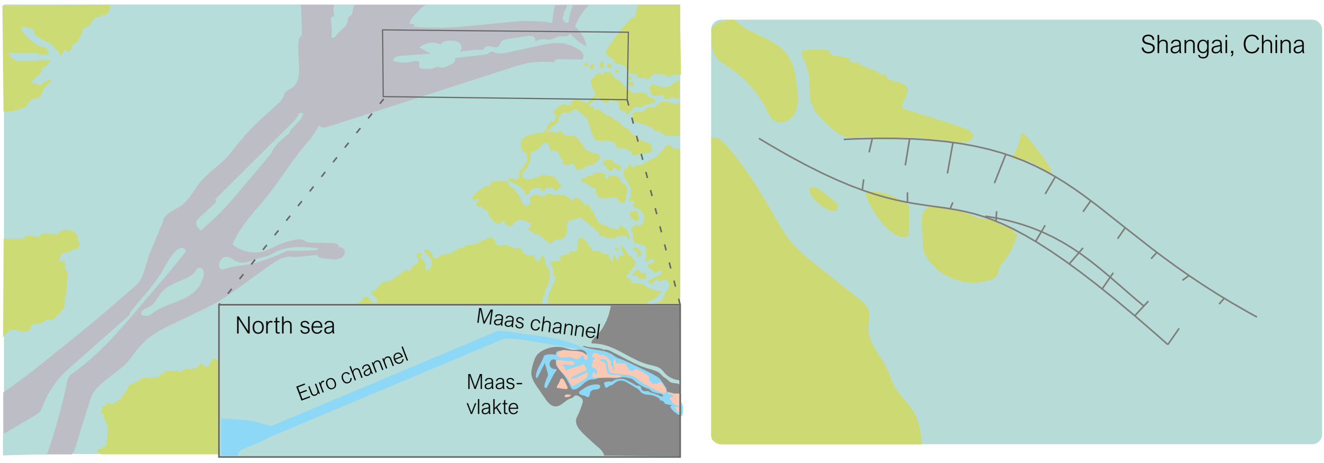

Figure 1.16: Left: Euro-Maas Channel, Rotterdam (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0); right: Deep Water Navigation Channel, Shanghai (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Turning basin

A turning basin is a wider water body inside a port or a canal where ships can turn around, or have space to turn a sharp corner (Figure 1.17).

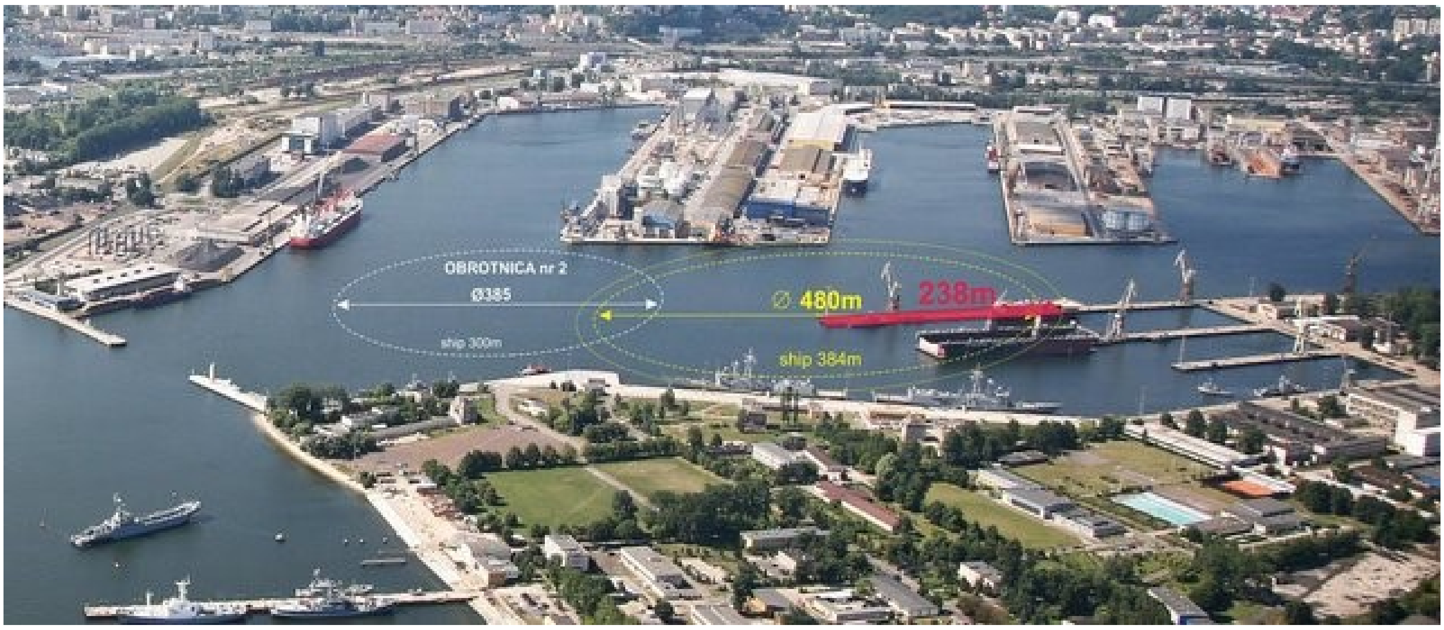

Figure 1.17: Turning basins in the harbour of Gdynia, Poland (Visualization of the concept of redevelopment of the turning basin No. 2 in the port of Gdynia by www.portalmorski.pl is licenced under CC BY 4.0).

Berth

A berth is a part of a terminal where individual ships are loaded or unloaded (Figure 1.18). In general, it is the combination of the part of the harbour where the ships are moored to be loaded or unloaded, a mooring facility and a land-connection (quay or jetty).

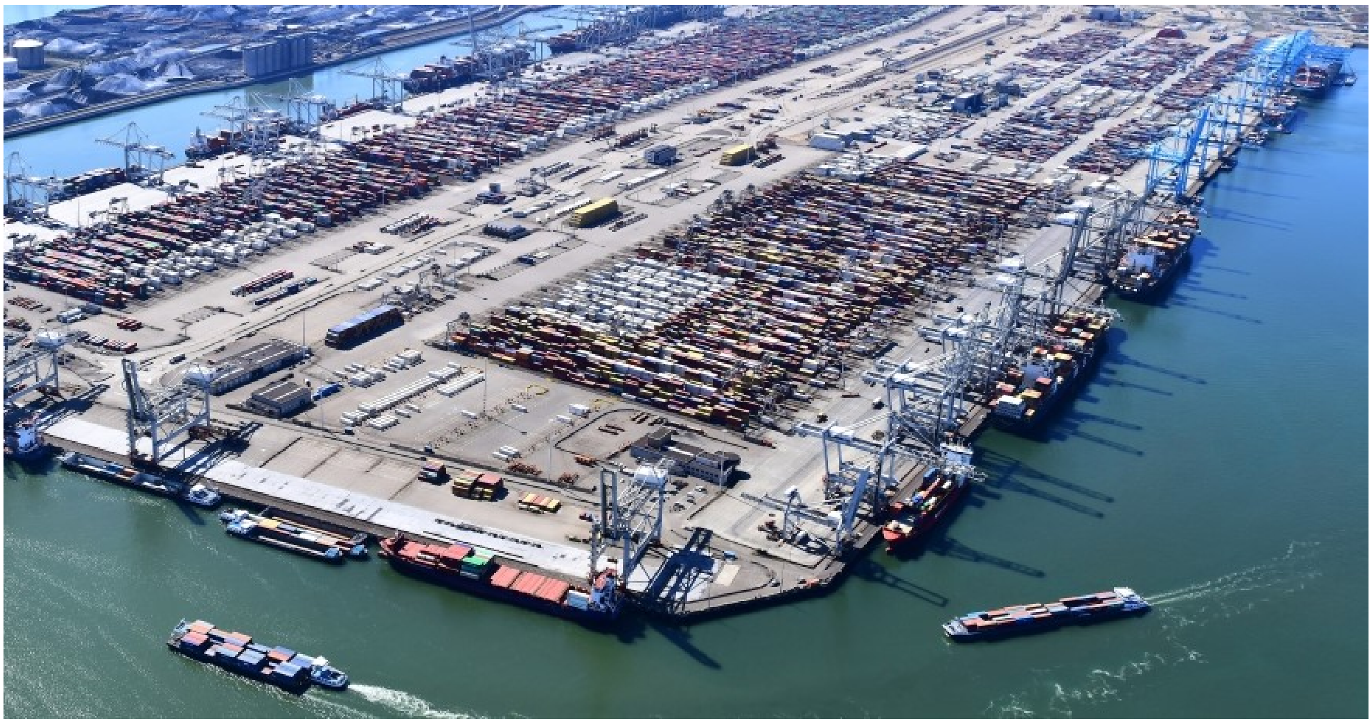

Figure 1.18: Berthed container ships in the Port of Rotterdam (by Europe Container Terminals (ECT) is licensed under CC BY-NC-SA 4.0).

Quay

A quay is a strip of land or a land-bordering structure where cranes and other loading and unloading facilities operate. There are many different structural concepts (Figure 1.19). In case of a vertical or almost-vertical separation between land and water, the soil-retaining structure is called quay wall (Figure 1.19, left).

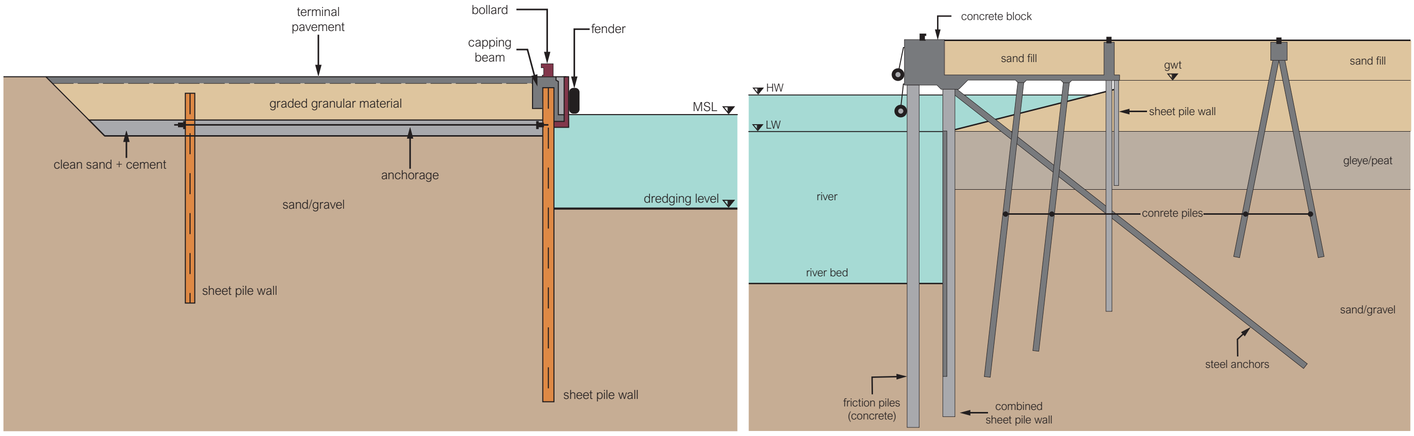

Figure 1.19: Examples of quay structures (by TU Delft – Ports and Waterways are licenced under CC BY-NC-SA 4.0).

Jetty (or pier)

A pier or jetty is a shore-connected structure over water to which vessels can be moored. In a port, a jetty may include one or more pipelines or other loading and unloading facilities (Figure 1.20, left). In a marina (harbour for yachts), it is a walkway to which boats are tied (Figure 1.20, right).

Figure 1.20: Left: Oil jetty, Total refinery, Milford Haven (by Richard Webb is licenced under CC BY-SA 2.0); right: Marina jetty (by pxhere.com is licenced under CC0 1.0).

Inland terminal

Apart from terminals at seaports, inland terminals are increasingly used, mainly for logistical purposes such as temporary storage, load redistribution, transhipment, transfer to another transport mode, etc. Such inland terminals are usually smaller than the ones in seaports (Figure 1.21).

Figure 1.21: Inland container terminal at Veghel, the Netherlands (https://beeldbank.rws.nl, Rijkswaterstaat).

Locks

A lock generally separates two bodies of water that differ in water level (Figure 1.22, left) and/or salinity (Figure 1.22, right). A lock enables vessels to move from one body of water to another. The main components are two (sets of) water-retaining doors and a lock chamber in which the water level can safely be adjusted from one level to the other. Higher water level differences may be covered by a series of locks (Figure 1.23).

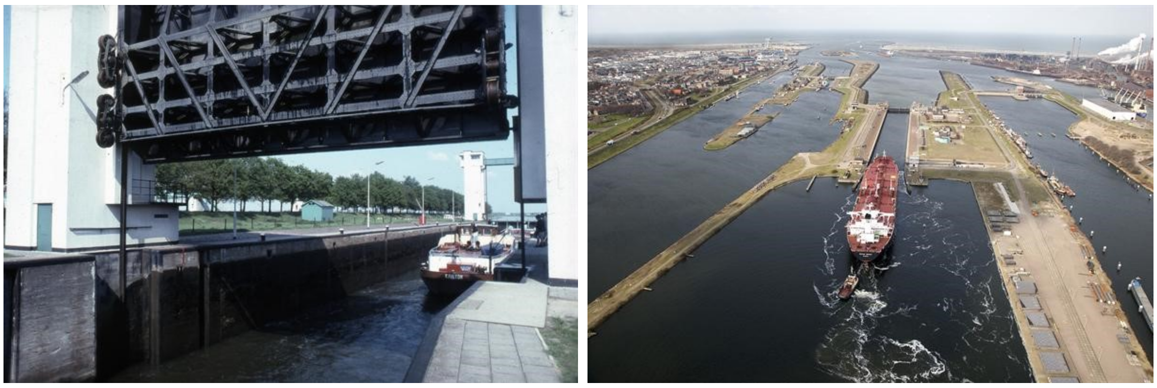

Figure 1.22: Left: Lock in the River Maas at Lith (https://beeldbank.rws.nl, Rijkswaterstaat, by: Hans van Oostveen); right: Sea lock complex at IJmuiden (https://beeldbank.rws.nl, Rijkswaterstaat, by: Fotostudio Honing Beverwijk).

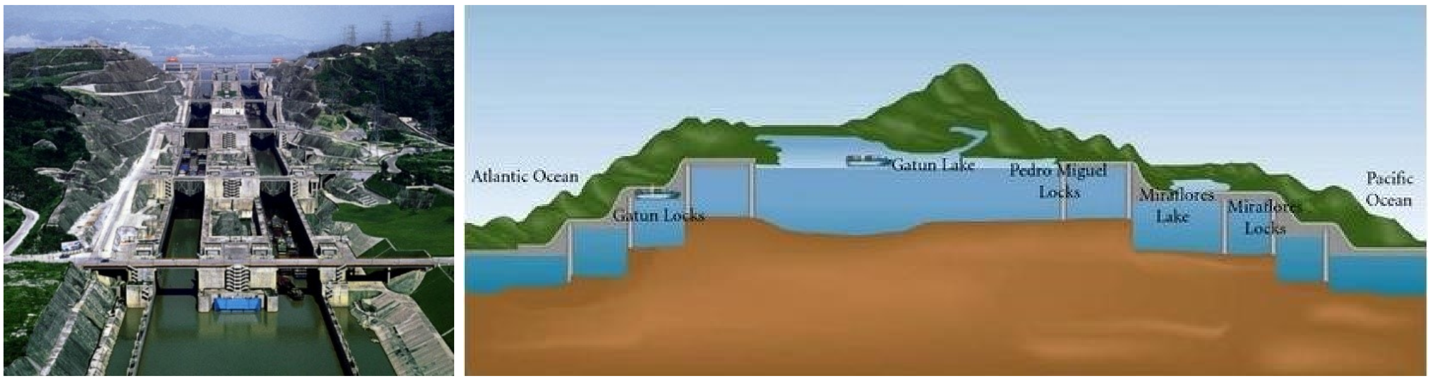

Figure 1.23: Left: 5-step lock system near the Three Gorges Dam, China (by Fan et al. (2015), is licenced under CC BY-NC-ND 4.0); right: Schematic of the Panama Canal (by Rabelo et al. (2012), is licenced under CC BY 3.0).

In some cases alternative techniques are applied to overcome height differences, such as ship lifts (Figure 1.24, left) or inclined slopes (Figure 1.24, right).

Figure 1.24: Left: Ship lift at Scharnebeck, Germany (by Holger Ellgaard is licenced under CC BY-SA 3.0); right: Inclined slope of Ronquires, Belgium (by Jean-Pol Grandmont is licenced under CC BY-SA 3.0).

Bridges

Bridges across waterways can either be fixed or movable (Figure 1.25). In canals with a fixed water level, a fixed bridge has a constant air draught, but in rivers the varying water level makes this quantity variable. In this case, a minimum air draught is guaranteed for a given percentage of time. Depending on the type, movable bridges have no air draught limitation or a high one. In order to limit the hindrance to traffic crossing the river or canal, opening times can be restricted. This may lead to waiting times for ships using the waterway.

Figure 1.25: Left: Fixed bridge across the Suez Canal (by Aashay Baindur is licenced under CC BY-SA 3.0); right: Movable bascule bridge (by Tvx1 is licenced under CC BY-SA 4.0).

1.2.3 Operations

Actors

Important actors in waterborne transport are:

- *shippers* – parties that ship goods from one place to another,
- *forwarders* – parties taking care of land transport (usually hired by the shipper),
- *shipping lines* – parties that operate sea-going and inland shipping vessels (Figure 1.26),
- *shipping agents* – intermediaries between shipping lines and ports,
- *port operators* – parties that coordinate the activities in a port,
- *pilots* – parties that assist vessels sailing from deep water into the harbour,
- *tugboats* – parties that assist vessels with near/in-port manoeuvring by pushing (by direct contact) or pulling them (by means of a tow line),

Figure 1.26: Shipping lines; left: Sea-going (Maersk Triple E by Igor Mak is licenced under CC0 1.0); right: Inland (Hendrik - ENI 02332477, Noord rivier, Dordrecht by Alf van Beem is licenced under CC0 1.0).

- *linesmen* – parties that assist vessels with efficient and safe (un)mooring by taking mooring lines from the ship's crew and making sure the ship is safely secured/released,
- *stevedores* – parties that take care of loading/unloading and storage of goods in a port,
- *waterway authorities* – parties responsible for design, maintenance and management of waterways and ports,
- *traffic control* – parties assisting vessels in waterways, harbours, (Vessel Traffic Service (VTS)),
- *lock masters* – parties taking care of operating lock passages,
- *boat master* – captain on sea-going vessels and skipper on inland vessels

Actors may have different, sometimes even conflicting interests. A terminal operator may wish to maximise berth occupancy, but this is bound to increase waiting times, which is not in the interest of shippers. A lock master may wish to maximise the number of vessels per locking cycle, but that too leads to longer waiting times. Operation policies, such as avoiding too high (suboptimal) berth occupancies, or maximising lock passage time, can help deal with this kind of conflicting interests.

Fleet

The fleet is a determining factor for the design of ports and waterways. Facilities tend to be adapted to the demands of shipping, rather than the other way around. The fleet consists of a wide variety of vessels, such as general cargo vessels (Figure 1.27), dry bulk vessels (Figure 1.28), liquid bulk vessels (Figure 1.29), container vessels (Figure 1.30), car-carriers (Figure 1.31) and cruise ships (Figure 1.32).

Figure 1.27: General cargo vessels; left: Sea-going (Cargo Vessel Nikiti II by Hermann Hammer is licenced under CC BY-SA 4.0); right: Inland (SchiffeMaxau by Ikar.us is licenced under CC BY 2.0).

Figure 1.28: Dry bulk carriers; left: Sea-going (Sabrina I cropped by Nsandel is licenced under CC0 1.0); right: Inland (Barge Ship Boat by needpix.com is licenced under CC0 1.0).

Figure 1.29: Liquid bulk carriers; left: Sea-going (Sirius Star 2008e by Navy.mil is licenced under CC0 1.0); right: Inland (Inland tanker vessel by BoH is licenced under CC BY-SA 3.0).

Figure 1.30: Container vessels; left: Sea-going (CSCL Globe at Felixstowe, UK by Keith Skipper is licenced under CC BY-SA 2.0); right: Inland (Rhine Barge Paradox opposite Port Louis by Charles01 is licenced under CC BY-SA 3.0).

Figure 1.31: Car-carriers; left: Sea-going (Car carrier Artemis Leader by Tvabutzku1234 is licenced under CC0 1.0); right: Inland (Barge with cars by Hu Totya is licenced under CC BY-SA 4.0).

Figure 1.32: Cruise ships; left: Sea-going (Carnival Freedom Cruise Ship by Rapidfire is licenced under CC BY-SA 3.0); right: Inland (Small Cruise Ship Independence by Tony Hisgett is licenced under CC BY-SA 2.0).

Port operations

The port operations, i.e. the complex of activities needed to run a port, try to make optimum use of the facilities available. The efficiency of a port depends on the extent to which this is successful. Port operations therefore need to be analysed, a process that can be supported by a range of techniques, from verbal models (narratives of how things work) and simple rules of thumb, via queuing theory through to sophisticated simulation models. These techniques are discussed further in Chapter 2 and Part IV.

Anchoring and mooring

Anchoring is dropping one or more anchors to fix the ship to the bed of the waterbody it floats on. As anchoring is space-consuming this is only done outside harbours, at open sea (Figure 1.33, left). Mooring is tying a ship with ropes or cables to a berth (Figure 1.33, right) or mooring buoy.

Figure 1.33: Left: Vessels queuing to enter the Panama Canal on the Pacific side (image by FDV is licenced under CC BY-SA 4.0); right: Typical mooring scheme for sea-going vessels (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

1.3 System performance

Section 1.2.1, Section 1.2.2 and Section 1.2.3 introduced some general terminology and definitions related to the transport network and its elements, important infrastructure and relevant operations. The key challenge for port and waterway engineers is to develop and compare alternative strategies for the design and operation of these waterborne transport networks in order to create a system in which transport capacity, efficiency, safety and sustainability are in balance and meet pre-defined objectives in a well-balanced way. A key performance indicator of waterborne transport networks is its overall capacity.

Terminal throughput and capacity

A terminal's throughput describes the amount of cargo (in tons or Twenty Feet Equivalent Units (TEU)) or the number of vessels that it handles over time. Throughput includes the handling of imports, exports and transhipments. A terminal's capacity indicates the maximum throughput it can handle over a given period. This capacity or maximum throughput can be derived by looking at the terminal's infrastructure, viz. available quay length, class of vessels that can be serviced, number of cranes available for (un)loading, theoretical crane (un)loading capacity, available storage capacity, capacity of hinterland connections, et cetera.

Theoretically the annual capacity of a terminal can be derived by looking at its mean hourly (un)loading capacity (averaged over a long period) × 24 (hours/day) × 365 (days/year). However, in practice there are many factors that cause the terminal's actual capacity to be lower: viz. the terminal's operational hours may be less than the theoretical 24 × 7 × 365 maximum, the available operational hours may not be fully available for (un)loading due to time consumed by (un)mooring, administrative tasks, bunkering, maintenance and weather-related downtime. Gaps in vessel arrival patterns may furthermore leave terminal equipment temporarily idle, et cetera.

While terminal operators might like to strive for maximum berth occupancy, to ensure that their often expensive (un)loading equipment is used to its full potential, on the other hand, for vessel operators high berth occupancies typically lead to queue formation and extensive delays. So rather than striving for maximum berth occupancy, which primarily suits the interests of the terminal operator, it is probably more economical overall to balance the interests of the terminal and vessel operators. Such middle ground may be found by designing a terminal that can achieve a predefined throughput, with sufficient additional (un)loading capacity available to keep average vessel waiting times below, for instance, 10% of the average vessel service time (terminal 'service level').

Apart from balancing capacity and efficiency, other aspects related to safety and sustainability may influence the overall design. Many of the aspects that influence terminal capacity are in fact influenced by properties of the connecting waterways and in-port water areas and the traffic that makes use of these.

Waterway traffic: density, intensity, capacity, traffic load and time

The density (D) of traffic on an inland waterway is the number of vessels or Dead Weight Tonnage (DWT) per unit surface area or unit waterway length. The traffic intensity (I) is the number of vessels or amount of DWT that passes a particular cross-section (waterway section, lock) per unit time in both directions. The maximum possible intensity is the capacity (C) at that particular cross-section. The ratio I/C quantifies the traffic load (always ≤ 1).

Apart from vessel class, the operational capacity is another important attribute of a waterway. It is defined as the maximum number of vessels (or maximum amount of DWT) that can pass per unit time in one direction through the cross-section with the smallest capacity, taking into account all time losses (waterway 'service level').

Time losses on a waterway can be caused by:

- waiting times at locks and bridges,
- the nature of the waterway; not only the depth and width of the navigation channel, but also bends, constrictions and structures may influence currents and vessel speeds;
- the traffic arrangements, e.g. the number of shipping lanes, general traffic rules, or safety regulations;
- the fleet composition (vessel types and dimensions, volume pattern i.e. number of vessels per hour); irregularity of the volume pattern obviously influences waiting times;
- interaction with other vessels;
- wind, visibility and flow conditions.

Clearly, some time loss components depend on variations in the traffic intensity or on fluctuations in discharge and water levels. Hence the operational capacity is not an independent property of a waterway. It is related to time-varying traffic densities and vessel speeds, to waterway dynamics (hydro- and morphodynamics), et cetera.

A never-ending optimization challenge

In practice a port and waterway engineer may be tasked to design an individual terminal with a predefined 'service level', or likewise a specific element in a waterway, such as a channel section or a lock, for instance. While these design challenges are already complex in their own right, it is clear that ports and waterways should be viewed as parts of a coherent system that supports efficient, safe and sustainable waterborne supply chains, and that their integral design and operation is essential (see Figure 1.34).

The world's economy relies heavily on waterborne supply chains. Approximately 90% of all global trade is shipped by marine transport; according to UNCTAD/RMT/2019, the total tonnage is divided almost equally among containers, tanker trade, main bulks and other dry cargo. The overall efficiency of global supply chains is to a great extent determined by the in-port and hinterland transport networks to which they are connected.

A major challenge in the field of port and waterway engineering is the timely adaptation of water transport networks, and their associated infrastructure, to ever-changing external circumstances, such as increasing vessel sizes, developments in trade, political instability, climate change, increased focus on sustainability, the energy transition, autonomous shipping, digitalisation, etc. The energy transition of the inland waterway sector is gaining attention, with many ongoing studies regarding the transition to a zero-emission European inland navigation sector.

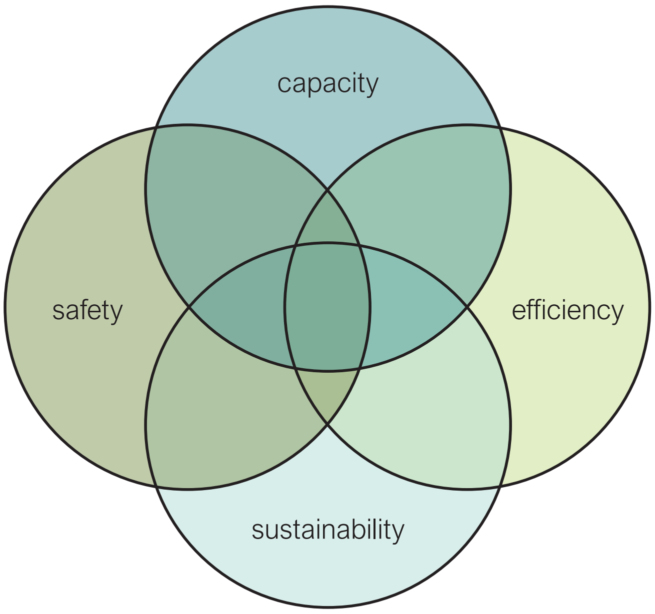

Figure 1.34: Integral design of waterborne supply chains, balancing capacity, efficiency, safety and sustainability (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The next chapter discusses various triggers of change in more detail. It furthermore elaborates the challenge of planning port networks under conditions of uncertainty. Several theoretical concepts to deal with this challenge are introduced. These concepts form a basic methodological groundwork for the analyses in Part II, Part III and Part IV.