Ports and Waterways
Navigating the changing world

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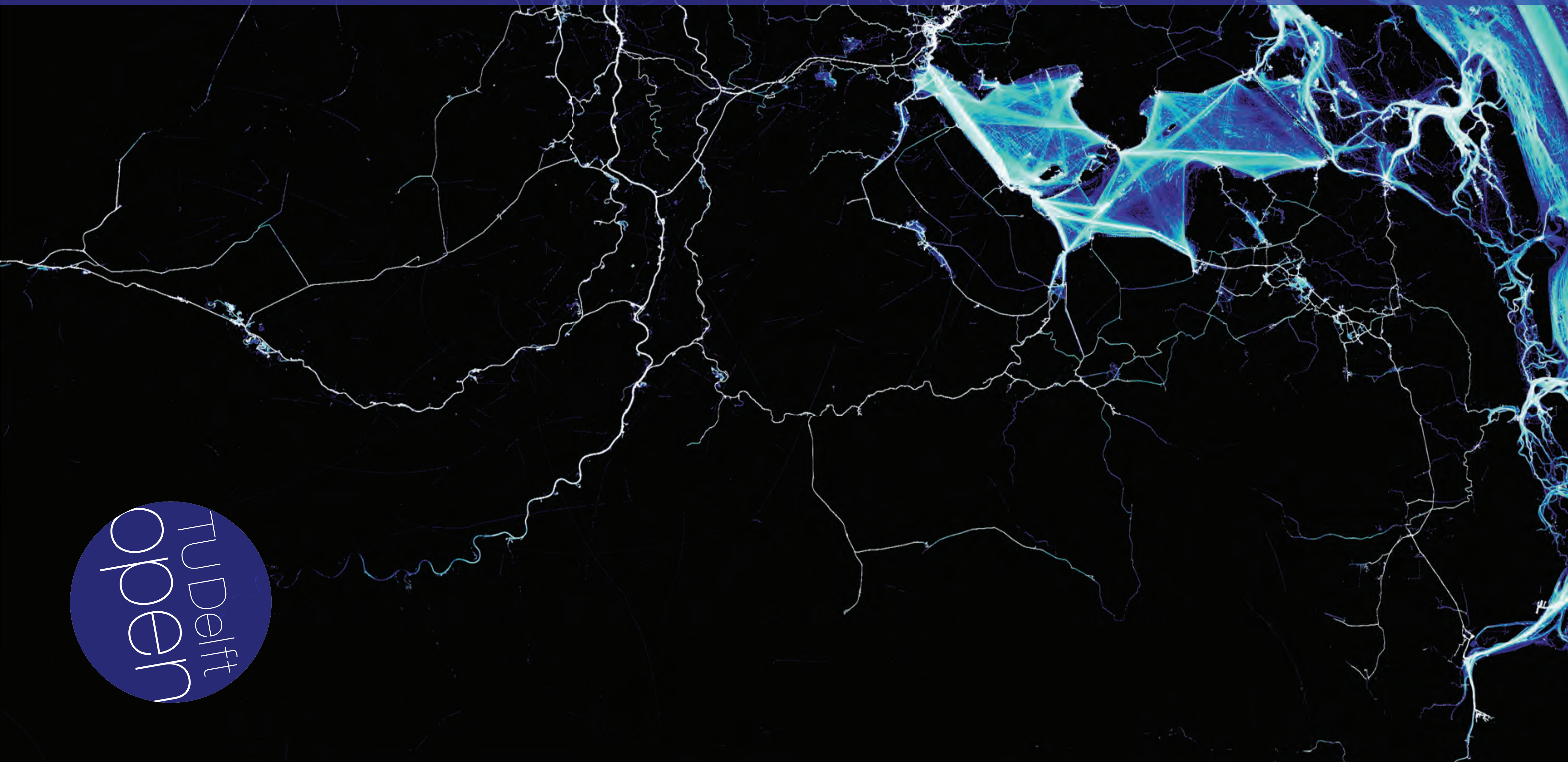
Ports and Waterways

Navigating the changing world

M. van Koningsveld, H. J. Verheij, P. Taneja and H. J. de Vriend



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Leading principle for writing:

The book 'Ports and Waterways – Navigating the changing world' enables students as well as professionals to develop and compare alternative strategies for the design and operation of waterborne supply chains.

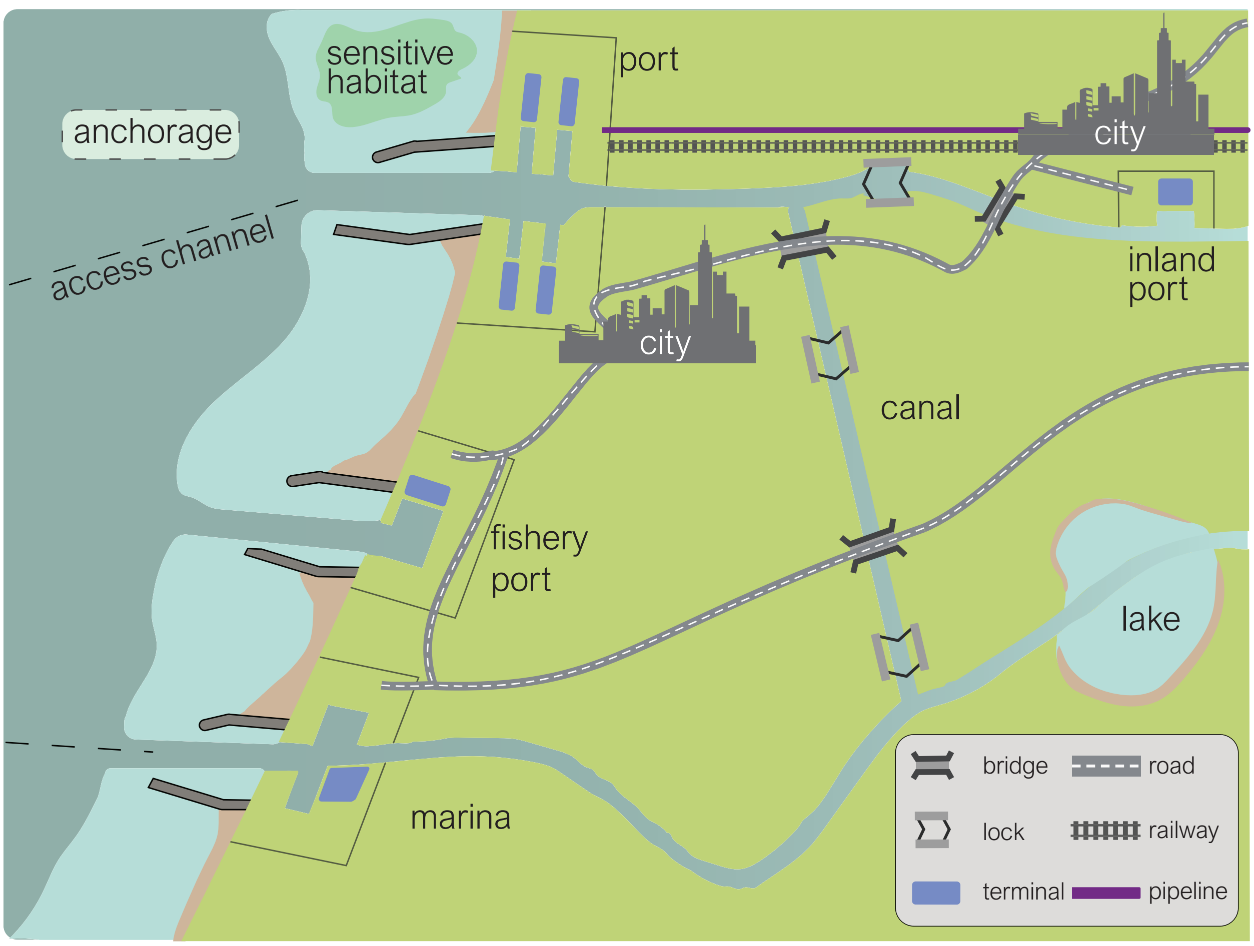
After reading this book you will be able to identify the important aspects of port and waterway systems (see figure), at various scale levels, and:

1. *execute performance analyses (with respect to pre-defined objectives for capacity, efficiency, safety and sustainability),*

2. *develop functional designs (in terms of required system elements and their order-of-magnitude dimensions), and*

3. *perform feasibility studies (how do the design choices affect cost and benefits, and how can the design be fit into the natural and social environment?).*

Furthermore you will be able to find, combine, and develop various simulation tools needed to quantify important aspects of these analyses.



Schematised port and waterway system

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Preface

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- Part I – Figure 1.4 – 'unloading' changed to 'loading' (in first inland terminal box)
- Part II – Figure 2.9 – changed y-axis label from '60M' to '0.80'
- Part II – Table 3.10 – updated E2/E2/n queueing table
- Part II – Section 4.4 – updated numbers in the example and minor textual changes
- Part II – Figure 4.16 – added a fender
- Part II – Figure 4.31 – added a fender
- Part III – Figure 1.22 – corrected details
- Part III – Figure 2.32 – switched 'left bank' and 'right bank' in lower panel
- Part III – Figure 3.5 – timing boundaries clarified in the figure and accompanying text
- Part III – Figure 3.6 – 'W_1' changed to 'W_l'
- Part III – Figure 3.8 – 't_u' changed to 't_i' (upper panel)
- Part III – Figure 3.10 – clarified figure
- Part III – Figure 3.12 – clarified figure
- Part III – Figure 3.14 – clarified figure
- Part III – Figure 3.15 – clarified figure
- Part III – Figure 3.16 – clarified figure
- Part III – Figure 3.28 – 'F_B' changed to 'H_B'
- Part III – Figure 4.5 – missing labels added
- Part III – Figure 4.6 – missing labels added
- Part III – Figure 4.7 – '$\overline{h}$' changed to 'h_0'

Contents

Preface

Motivation

Before you lies the book 'Ports and Waterways – Navigating the changing world', written by the Ports and Waterways team, part of the Civil Engineering and Geosciences faculty at Delft University of Technology. It integrates the content of a number of separate lecture notes we used in our teaching activities and updates this information where relevant. The integration reflects our vision that ports and waterways should be viewed as parts of a coherent system that supports waterborne supply chains, and that their integral design and operation is essential.

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/2020, the total tonnage is divided among containers (17%), main bulk (29%), other dry cargo (26%) and tanker trades (28%). 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. Large investments are required to maintain (and where possible improve) competitive positions. Optimising while markets continuously rebalance requires insight, skill, fundamental and applied research. Getting it wrong is not only very costly but may severely impact future competitiveness.

The design and operation of port and waterway systems is a complex challenge that involves many disciplines. External triggers force actors to continuously review whether their policies and positions will be sustainable. Often measures need to be taken to adapt to the changing world. Non-linear feedbacks that exist in and between these systems make it risky to rely on intuition and experience alone. Port and waterway professionals embrace this complexity and develop and compare alternative strategies for the design and operation of waterborne supply chains to support decision making. This requires a thorough understanding of the key elements of port and waterway systems, and their complex interactions, in order to create a system in which transport capacity, efficiency, safety and sustainability meet pre-defined objectives in a well-balanced way.

Target audience and scope

Initially, this book was conceived with students who pursue the Ports and Waterways specialisation at TU Delft in mind. However, thanks to the input from numerous experts and specialists while writing, and valuable knowledge over the state-of-the-art advancements in ports and waterways, we do not hesitate to recommend it also to professionals in the field of ports and waterways.

System optimisations may focus on changes to logistics, vessel dimensions, traffic management regulations as well as on port and waterway infrastructure. While these aspects are all important, this book focuses specifically on the functional aspects of infrastructure and fleet, on key hydrodynamic processes that influence operations, and on how these aspects together affect the performance of waterborne supply chains. After reading this book you will be able to develop and compare alternative strategies for the design and operation of waterborne supply chains:

1. execute performance analyses (with respect to pre-defined objectives for capacity, efficiency, safety and sustainability),
2. develop functional designs (in terms of required system elements and their order-of-magnitude dimensions), and
3. perform feasibility studies (how do the design choices affect costs and benefits, and how can the design be integrated into the social and natural environment?).

Different stakeholders have different interests when looking at the same system: a port authority may have different management objectives than a terminal operator, who in turn might have different management objectives than shipping lines, et cetera. On top of these direct stakeholders, the interests of silent stakeholders, like the general public and the environment, also need to be considered. While port and waterway engineers generally do not make the policy decisions that affect these interests, they should be able to inform the debate between decision makers and stakeholders with transparent and objective information.

Book structure

To introduce the reader into the multi-faceted topic of port and waterway engineering, this book is divided into four parts:

Part I provides a **General introduction** into the importance of waterborne supply chains and how they rely on a well-functioning network of ports and waterways. It defines several terms that are used throughout the book and discusses drivers that trigger a constant need for change. Finally, it introduces some theoretical concepts that form a basic methodological groundwork for specific analyses in the following parts. Part I is specifically targeted at readers who are new to the port and waterways topic, but also provides a concise but complete introduction that may be interesting to a wider range of professionals.

Part II addresses **Ports and terminals**. It highlights their importance as nodes in waterborne transport networks and discusses key aspects that should be considered while developing port master plans and port layouts. At the next level of detail, the dimensioning of individual terminals is discussed within the overall port layout. As an illustration, the key aspects of container supply chains are elaborated. Furthermore, we provide a basic guideline to develop a functional terminal design, specifying the required terminal elements and their order-of-magnitude dimensions for a given yearly throughput. Other terminal types are treated briefly, highlighting the specifics to be considered in their individual design.

Part III deals with the connections between the nodes of waterborne transport networks: **Waterways**. After discussing the importance of transport over water, guidelines for the functional design of waterways and waterway elements, such as locks and bridges, are provided. Furthermore, dimensions of water areas in sea and inland ports are addressed. Special attention is given to ship-induced water motions as they affect ship-waterway and ship-ship interactions. Finally, traffic management systems are discussed.

Whereas Part II and Part III deal with ports and terminals and waterways respectively, Part IV focuses on **System performance**. It gives numerous and varied examples of how to quantify parameters that are significant to the performance of ports and terminals, waterways and port and waterway systems. In Part IV, ample reference is made to available simulation tools, some of which have been developed at TU Delft. These tools help to quantify the analyses and make the results explorable and communicable.

We believe that this structure and the scope of the information provided will help current and future engineers to become valuable contributors to the interesting and important field of port and waterway engineering.

Prof. dr. ir. Mark van Koningsveld,
8th February 2023,
on behalf of TU Delft's Ports and Waterways team.

Part I

General introduction

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).

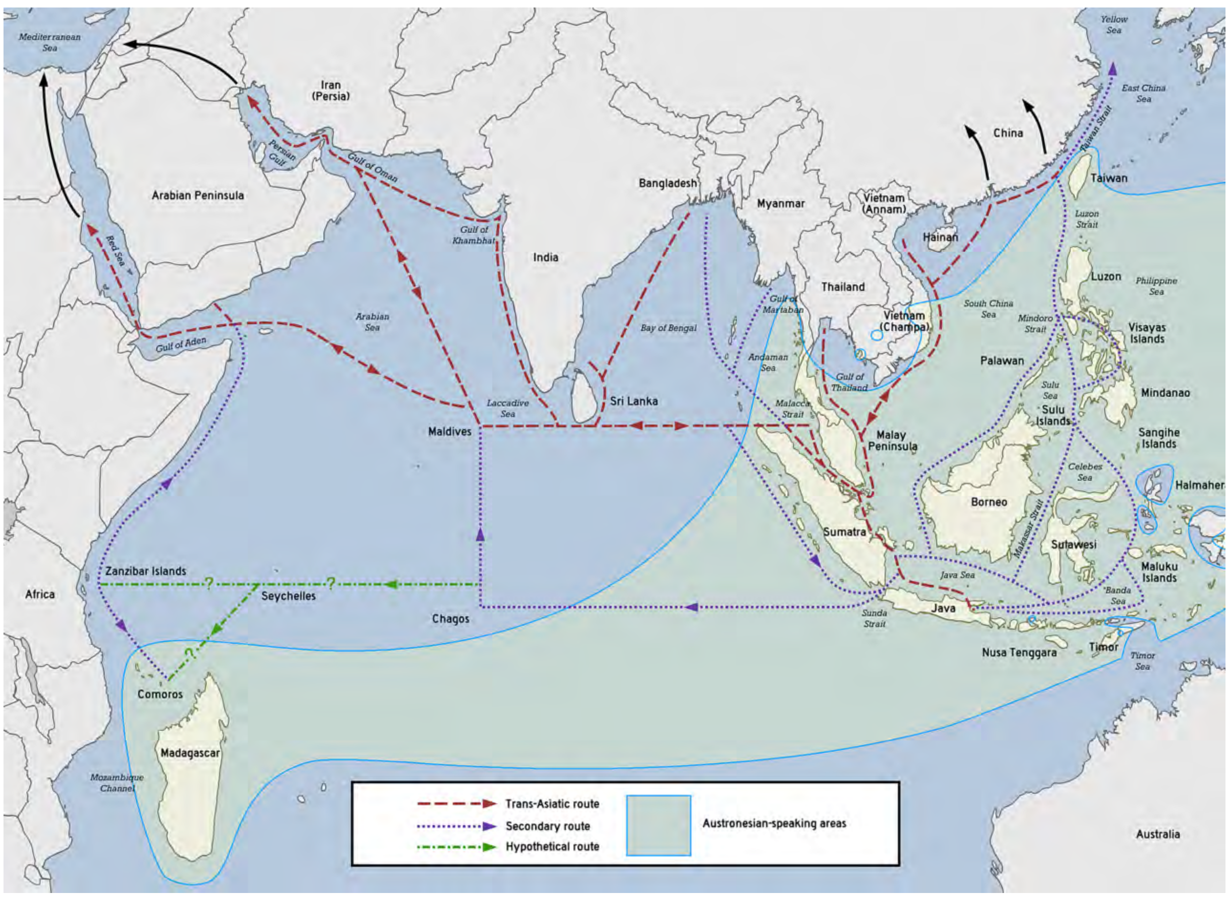


Figure 1.1: Austronesian maritime trade network in the Indian Ocean (by O. Soul is licenced under CC0 1.0).

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).

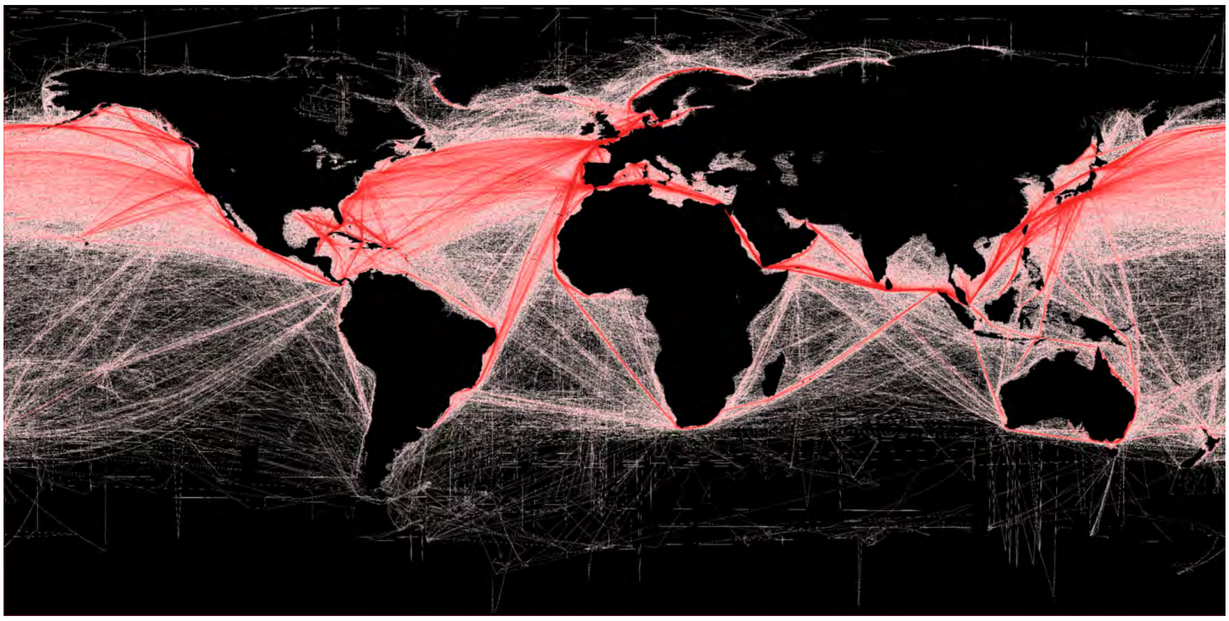


Figure 1.2: Present-day commercial shipping routes (by B.S. Halpern (T. Hengl; D. Groll) is licenced under CC BY-SA 3.0).

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.

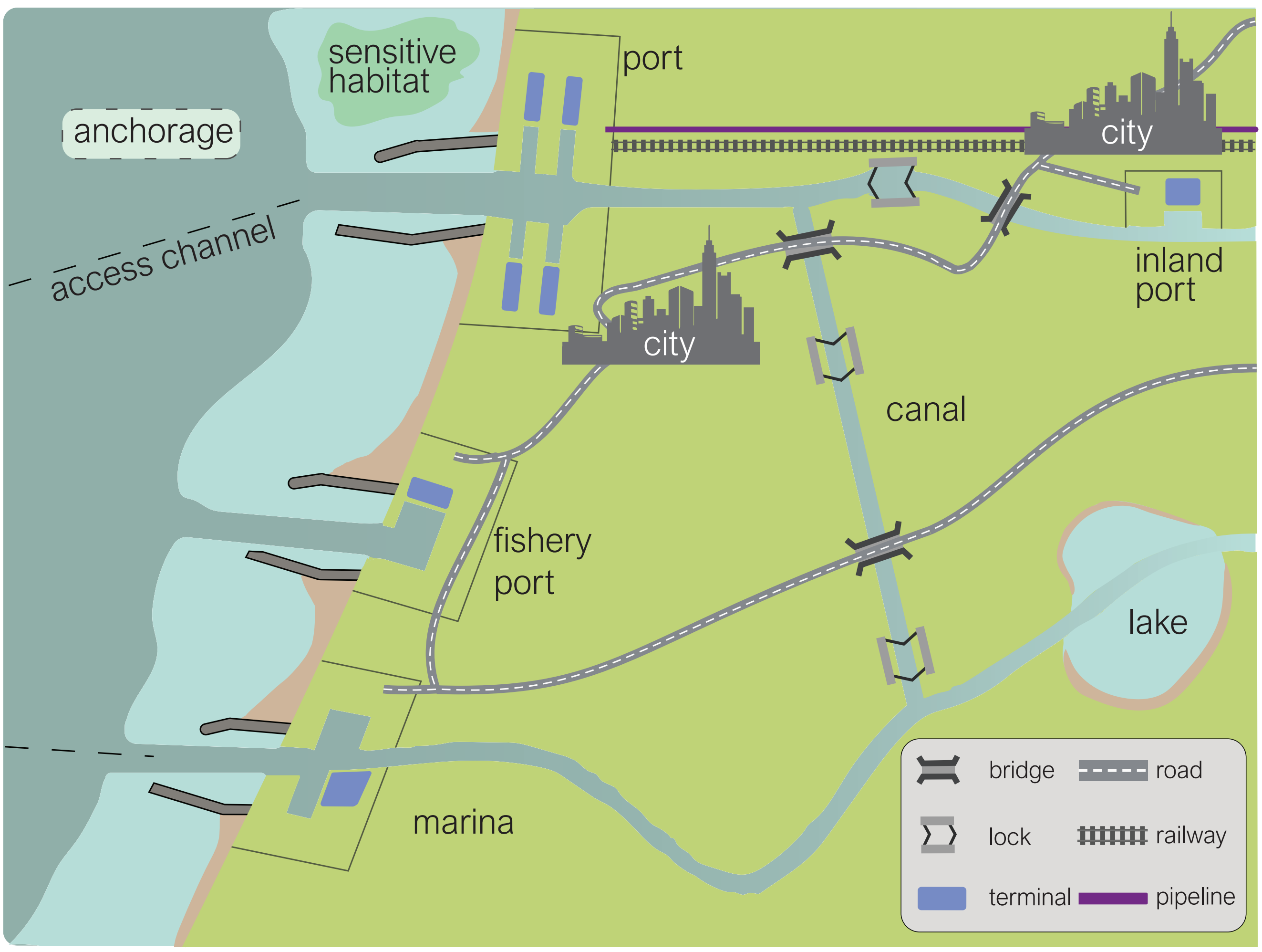


Figure 1.3: Elements of a transport network (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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).

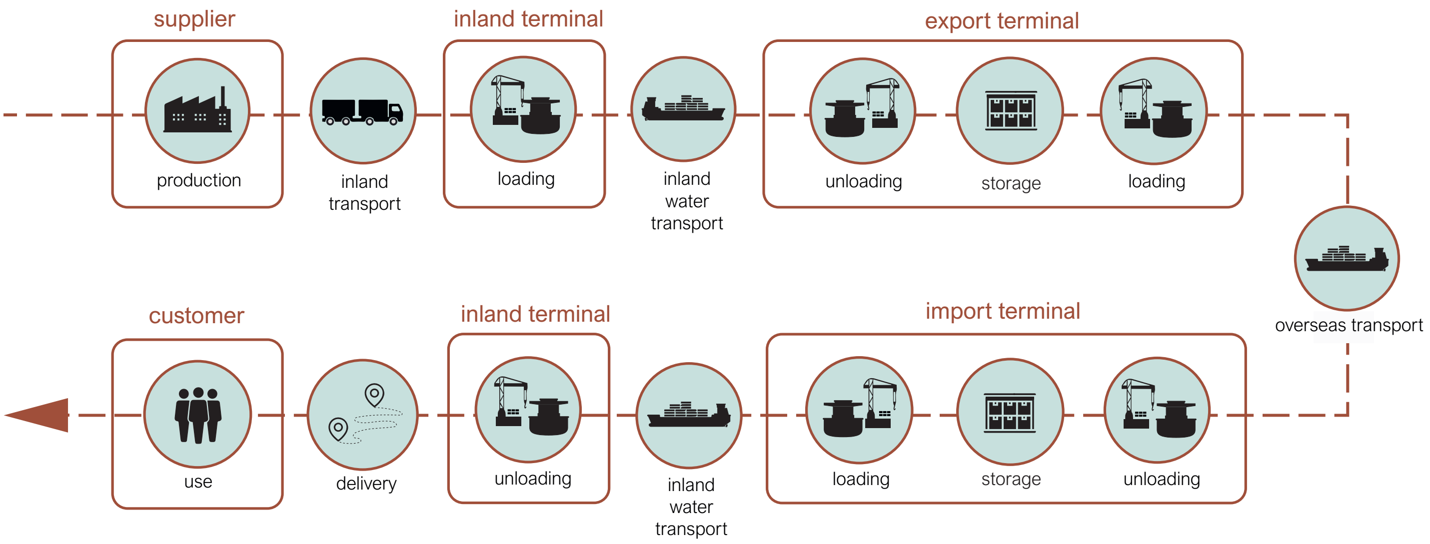


Figure 1.4: Schematics of an overseas supply chain (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

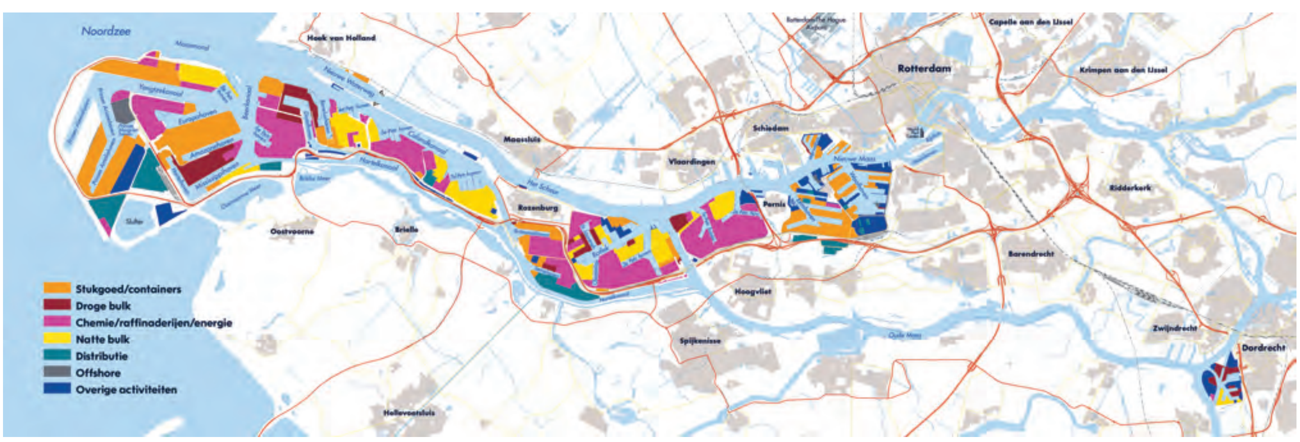


Figure 1.5: Overview of the Port of Rotterdam (by Port of Rotterdam is licenced under CC BY-NC-SA 4.0).

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.

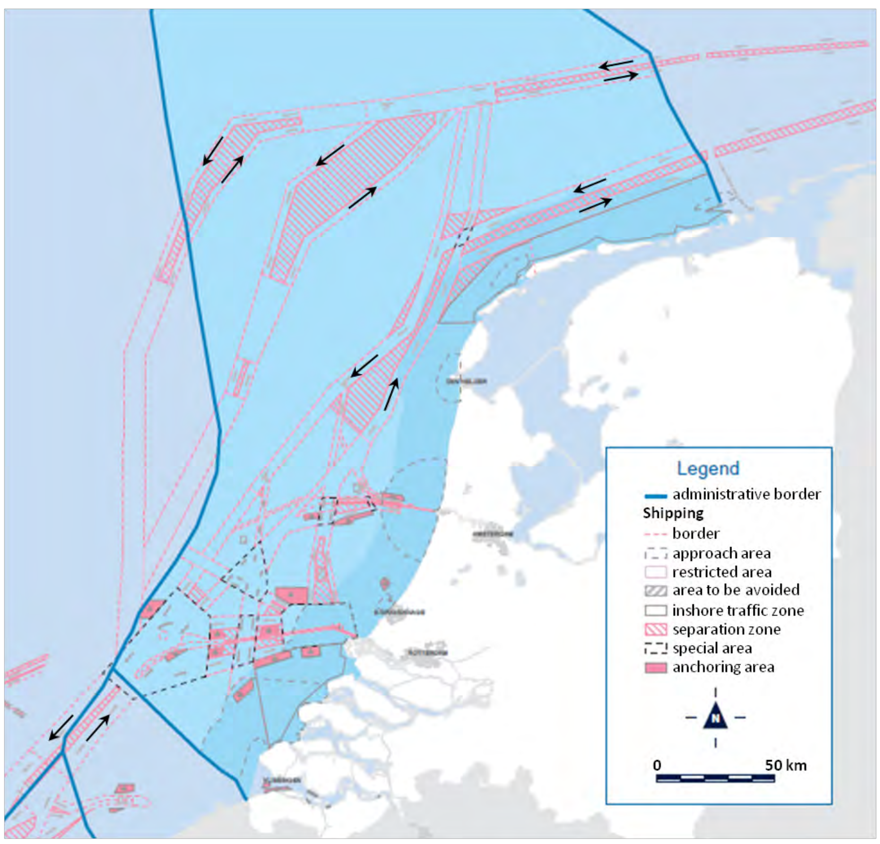


Figure 1.7: North Sea shipping lanes (by Noordzeeloket is licenced under CC0 1.0).

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.

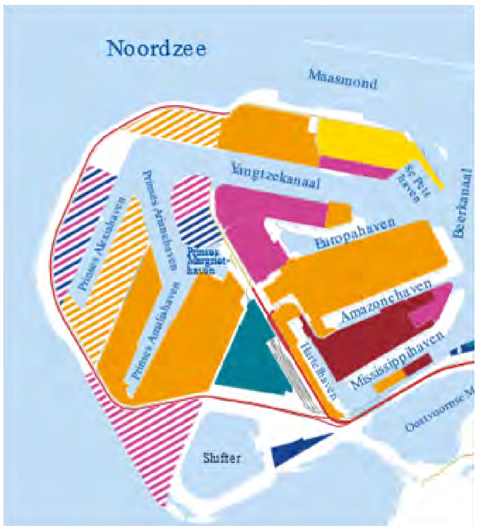


Figure 1.11: Left: The harbours of the Maasvlakte, Port of Rotterdam (RotterdamPort by Vorpzn is licenced under CC0 1.0); right: Overnight harbour Lobith (aerial imagery by the National Georegister (NGR) is licenced under CC BY 4.0).

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).

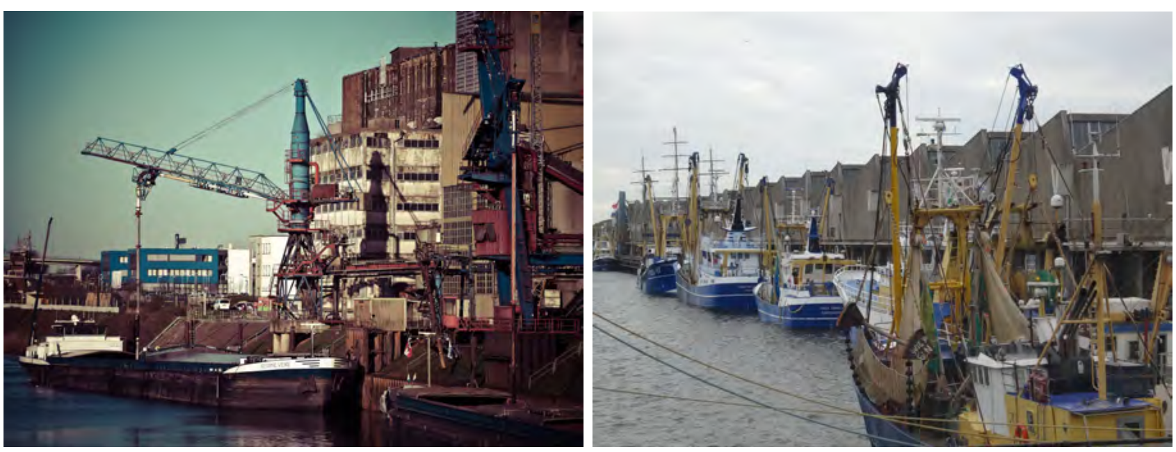


Figure 1.15: Left: River barge terminal (image by pxhere.com is licenced under CC0 1.0); right: Fisheries terminal, Scheveningen (Scheveningen Haven by harry_nl is licenced under CC BY-NC-SA 2.0).

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).

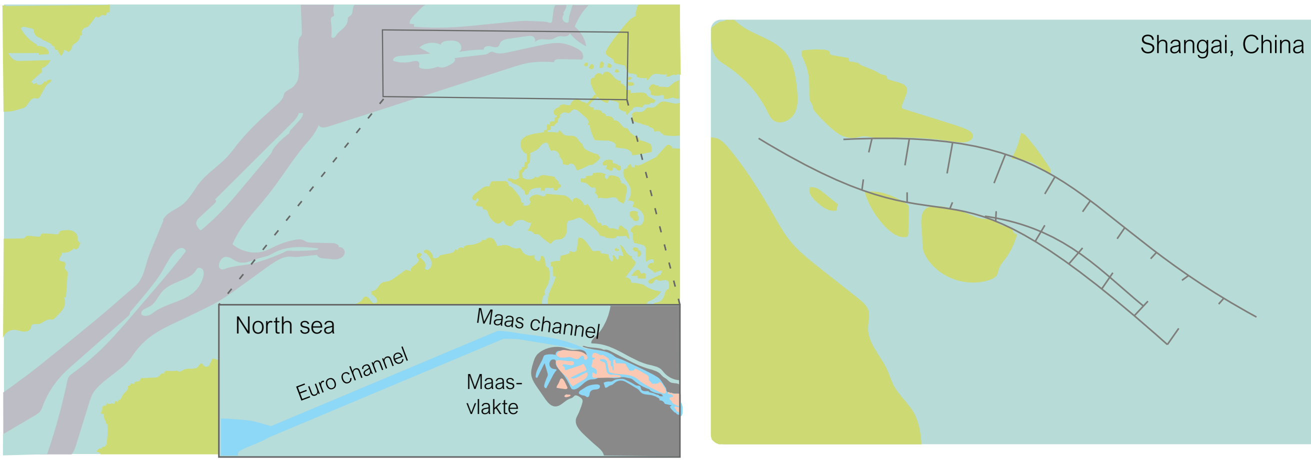


Figure 1.16: Left: Euro-Maas Channel, Rotterdam (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0); right: Deep Water Navigation Channel, Shanghai (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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).

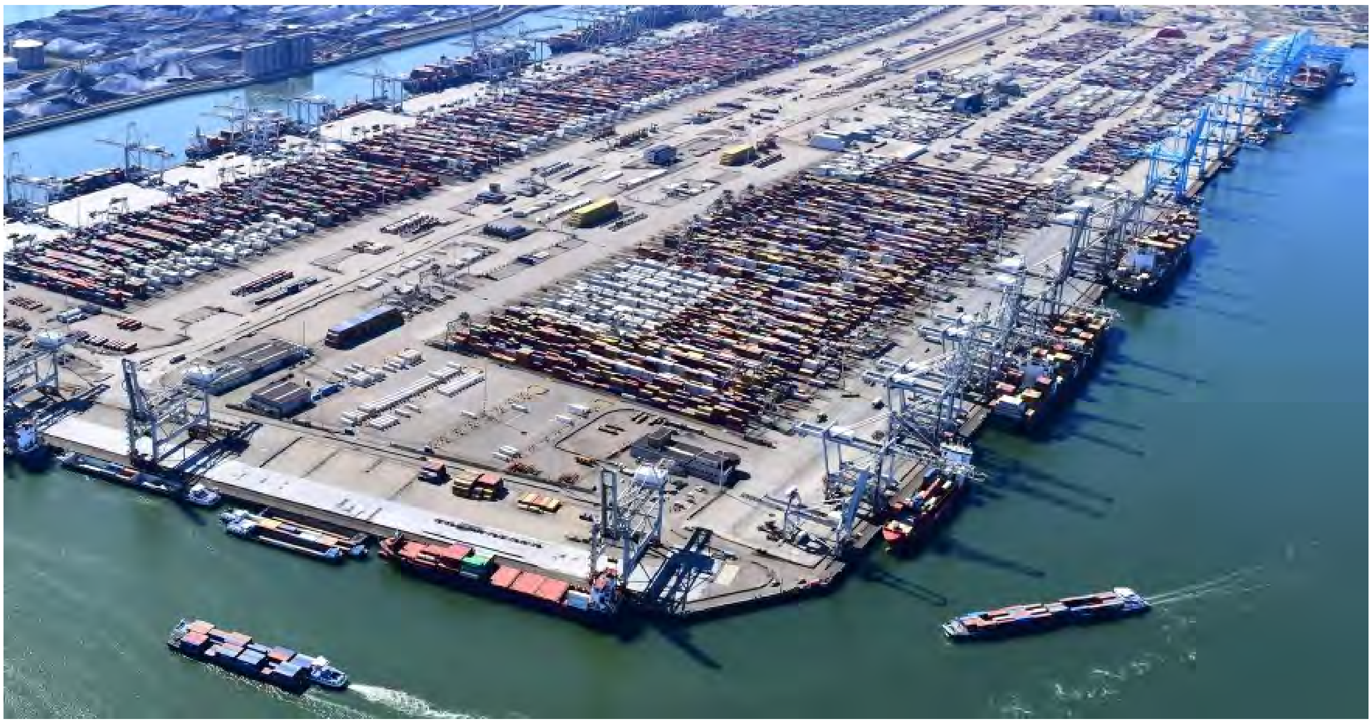


Figure 1.18: Berthed container ships in the Port of Rotterdam (by Europe Container Terminals (ECT) is licensed under CC BY-NC-SA 4.0).

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).

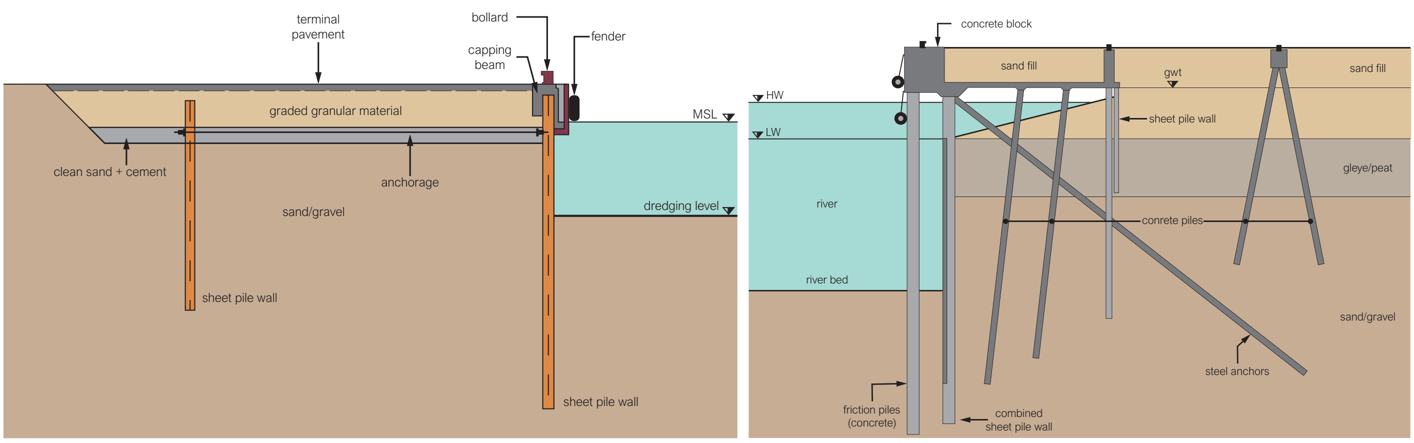


Figure 1.19: Examples of quay structures (by TU Delft – Ports and Waterways are licenced under CC BY-NC-SA 4.0).

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).

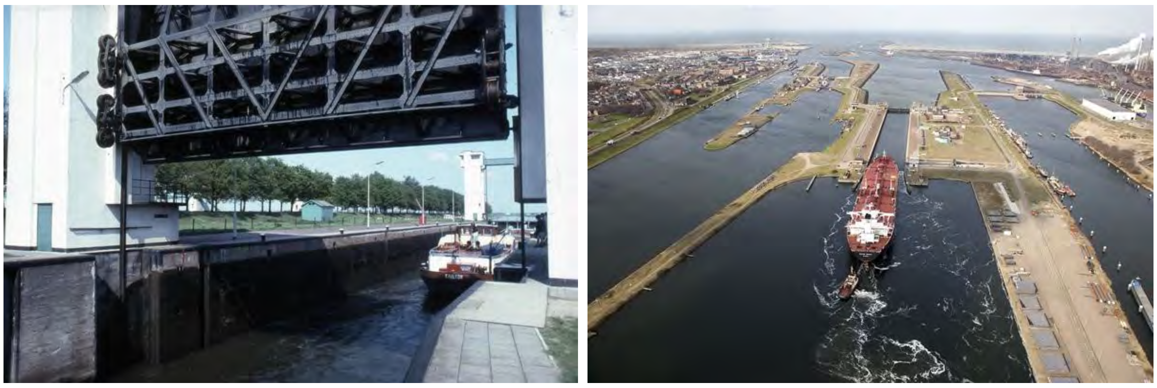


Figure 1.22: Left: Lock in the River Maas at Lith (https://beeldbank.rws.nl, Rijkswaterstaat, by: Hans van Oostveen); right: Sea lock complex at IJmuiden (https://beeldbank.rws.nl, Rijkswaterstaat, by: Fotostudio Honing Beverwijk).

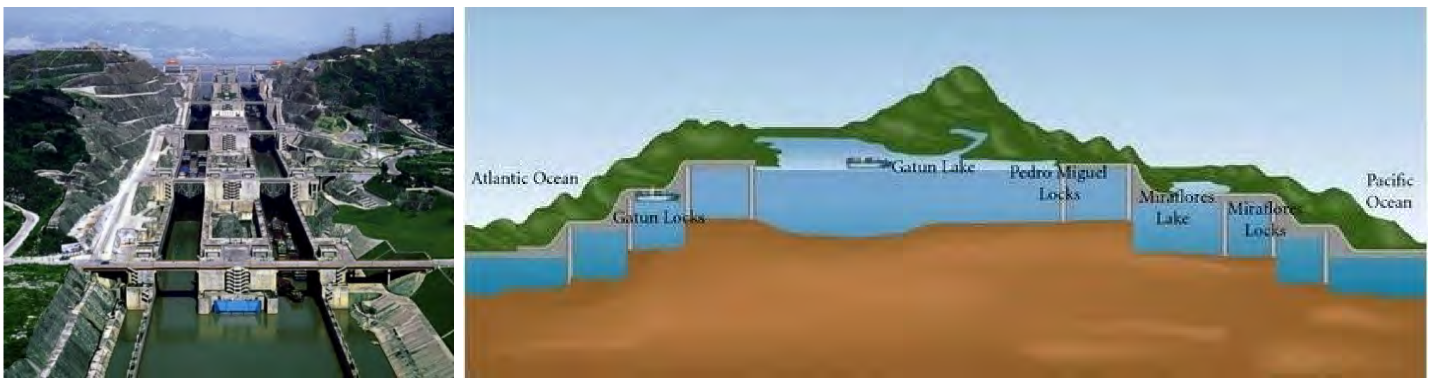


Figure 1.23: Left: 5-step lock system near the Three Gorges Dam, China (by Fan et al. (2015), is licenced under CC BY-NC-ND 4.0); right: Schematic of the Panama Canal (by Rabelo et al. (2012), is licenced under CC BY 3.0).

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) $\times$ 24 (hours/day) $\times$ 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 $24 \times 7 \times 365$ 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.

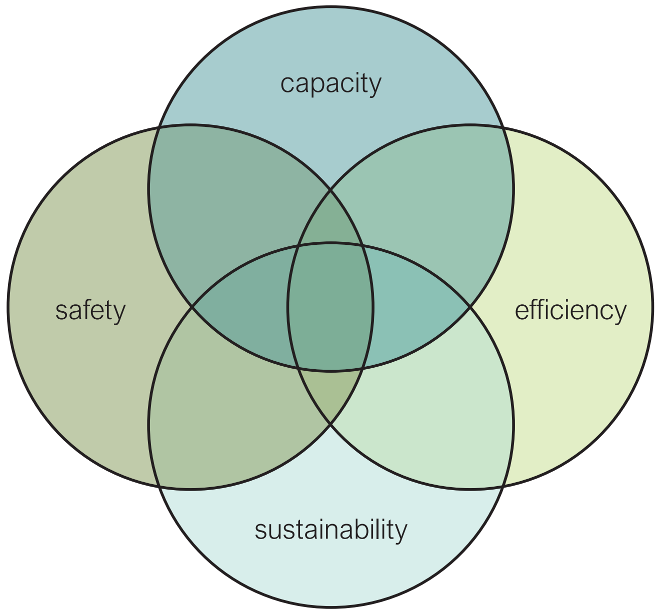


Figure 1.34: Integral design of waterborne supply chains, balancing capacity, efficiency, safety and sustainability (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

2 A constant need for change

2.1 Triggers of change

Ports and waterways are built for the long term and involve major investments. Moreover, they function in a highly competitive environment, with competitors like nearby ports and other transport modalities. Making the right choices at the right moment is therefore key to the success of a waterborne transport network. This requires, however, looking into the future of a rapidly changing world. The ability to make sensible future projections and take the right decisions based on them is the name of the game in port and waterway development. The possible changes relevant to port and waterway development are many and they are all uncertain:

- technological developments (vessel size, energy transition, communication, autonomous shipping, big data),
- economic and political changes (economic cycles, global economic power shifts, regional changes in Gross Domestic Product (GDP), interest rates, fuel prices),
- changes in society (appreciation of e.g. environmental issues, consumption patterns, availability of labour, demographic changes),
- ongoing environmental changes (erosion/sedimentation, water quality),
- climate change (temperature, river discharge, sediment transport, ecosystem),
- accelerated relative sea level rise (height of quays and other structures, bridge height, flood protection),
- crises and calamities (economic, health, environmental, geopolitical).

In the next subsections we will examine these in more detail, focusing on their relevance to the development of supply chains and port and waterway infrastructure.

2.1.1 Technological developments

Technological developments may have a major impact on port and waterway development, but they are also notoriously difficult to foresee. Suppose 50 years ago we would have had to plan a waterborne transport network with a 50-year planning horizon. It would have been impossible to foresee the increase in vessel size (Figure 2.1), or the growth of container transport, or the spectacular development of communication technology. Robustness (ability to cope with small changes) and adaptability (ability to cope with larger changes) are the only possible responses to this kind of developments.

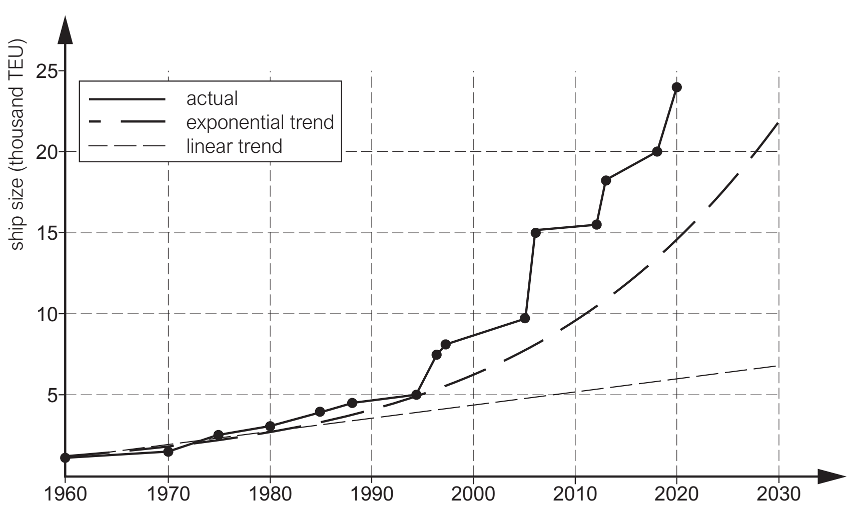


Figure 2.1: Container vessel size increase over time (seagoing vessels) (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Despite the inherent uncertainties, there are ongoing developments that *can* be projected into the future with a certain degree of confidence, such as the upcoming energy transition, developments in port-ship communication, automation and autonomous shipping, artificial intelligence and big data.

Energy transition

Approximately 90% of the world's trade is carried by sea. It's by far the cheapest way to transport large volumes of goods and raw materials around the world. In its third Greenhouse Gas (GHG) Study in 2014, the International Maritime Organization (IMO) estimated all shipping on average emitted 1.015 million tons of CO_2 per year, for the period of 2007 – 2012. This accounts for 3.1% of the estimated global annual CO_2 emissions. Similarly this study estimated all shipping on average emitted 20.9 million tonnes of NO_x (as NO_2) and 11.3 million tonnes of SO_x (as SO_2). These estimates represent 15% of the NO_x and 13% of the SO_x globally emitted by anthropogenic sources, as reported in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5).

The relatively high contribution to global NO_x and SO_x emissions can be attributed to the industry's use of cheaper, lower-quality, high-sulphur fuel oil (Figure 2.2). In 2020 the IMO introduced restrictions to the sulphur and nitrogen content of fuel, which are no longer met by high-sulphur fuel oil. Ships will therefore have to move over to other types of fuel or take special measures, like installing scrubbers, to reduce emissions. Figure 2.7 shows a Goldman Sachs projection of how these restrictions may affect the fuel mix.

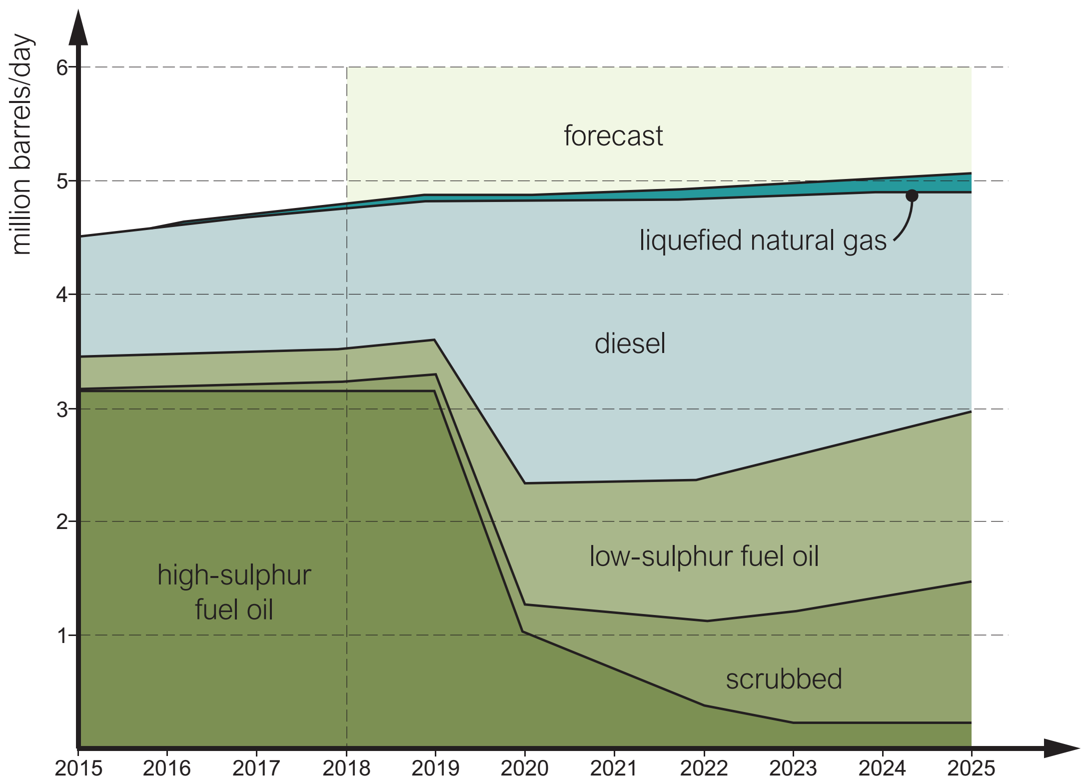


Figure 2.2: Expected evolution of the fuel mix in maritime shipping, in million barrels per day (reworked from www.economist.com by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Changes in the fuel mix may affect the competitiveness of Maritime and Inland Water Transport (IWT) compared to other modalities, or the competitiveness of one corridor over another. Ports will need to adapt their bunkering facilities anticipating future demand. But there is a long list of fuel and other energy carriers that can be used in shipping, and which one will prevail is as yet uncertain. The ones most commonly considered for the short term are LNG, Electricity, Biodiesel and Methanol. Other fuels that could play a role in the future are Liquified Petroleum Gas (LPG), Ethanol, Dimethyl Ether (DME), Biogas, Synthetic Fuels and Hydrogen (particularly for use in fuel cells). All these energy carriers are virtually sulphur-free, and can serve to comply with the new sulphur content regulations. They can be used either in combination with conventional, oil-based marine fuels, thus covering only part of a vessel's energy demand, or to completely replace conventional fuels.

For ports the energy transition presents risks, for instance when the industry moves to a different solution than initially anticipated. It also presents opportunities, however, to undertake new activities, such as creating production and blending areas for renewable fuels, or the production of synthetic fuels from imported hydrogen and captured carbon. If this leads to dismantling offshore oil and gas industry, there is a market for recycling offshore rigs and ships, as well as for supporting other offshore activities, such as the production of renewable energy in offshore wind farms.

It is fairly certain that the shipping industry will go through an energy transition in the coming years. But how this will take place exactly, and which choices will be made by the industry along the way, is still highly uncertain. Ports need strategic planning and adaptability to follow this transition.

Port-ship communication

Whenever ships come into port a whole range of administrative tasks need to be performed: customs declarations are needed for the ship's cargo and stores, immigration clearance is needed for crew, passengers and their baggage, import and export permits need to be arranged, et cetera. All these tasks are time-consuming and considered an administrative burden. Reducing this burden will increase the efficiency of maritime trade and transport.

Like in the case of the energy transition, significant changes are imminent in the way ports and ships exchange information. As of April 2019, national governments are required to introduce electronic information exchange between ports and ships, with the aim to increase the efficiency of the logistics chain. This mandatory requirement comes under the IMO Convention on Facilitation of International Maritime Traffic (FAL). It is a step toward just-in-time operations throughout the supply chain.

While it is fairly certain that information exchange between ports and ships will undergo large changes in the coming years, it is still uncertain which electronic system will eventually become dominant, and how this will affect other processes in the supply chain and the ports.

Autonomous shipping

Another spectacular innovation in the maritime (viz. seagoing and inland) industry is autonomous shipping. A fully autonomous vessel can observe and sense its environment, navigate and manoeuvre without human intervention. It can communicate with other ships, traffic control, waterway infrastructure and terminals. Autonomous shipping is driven by the need to make shipping safer, cheaper and more sustainable and is enabled by developments in sensor technology, telecommunication, artificial intelligence and computing, with improved digital connectivity and intelligence as a result.

Autonomous shipping has the potential to significantly lower transport costs, as it needs less manpower and the space for crew accommodation can be used for cargo. It can improve safety by reducing human error (about 75%

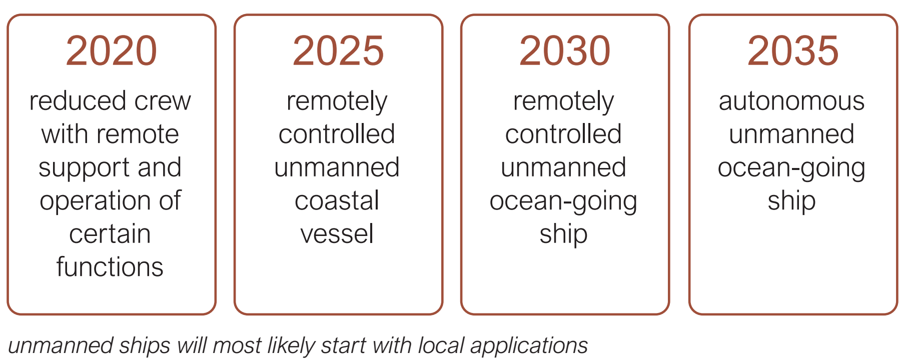


Figure 2.3: Evolution of autonomous shipping (modified from Rolls Royce, Autonomous ships – The next step by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

of maritime accidents are attributed to human errors), improve security by a reduced vulnerability to piracy, is less susceptible to crew shortage and strikes, and able to better integrate shipping in the transport system. Fuel saving through optimal steaming, the potential use of alternative fuels and zero-emission technologies, no ballast and less garbage and sewage are expected to make autonomous shipping more environmentally friendly.

Various parties around the world are working on autonomous shipping concepts. Rolls Royce, for instance, aims at launching its first unmanned ocean going vessel in 2025 (Figure 2.3). In the Netherlands, the first autonomous manoeuvring vessel trials were held in the North Sea in 2019, as part of the Joint Industry Project Autonomous Shipping.

Technologically speaking this development is already maturing, but its uptake in maritime transport lags behind. This is partly because an undisputable business case is still lacking and partly because this requires new international legislation and regulations regarding issues such as safety, insurances and emergencies. Increased digitalisation not only has benefits, but also presents risks (i.e. technical failure, hacking, etc.). Particular challenges are furthermore foreseen for the phase where conventional ships, smart ships and fully autonomous ships all make use of the same facilities.

For port and waterway engineers, the challenge is to figure out the interaction of such smart and autonomous ships with other vessels, the port infrastructure and assets for port operations such as piloting, tug support, berthing and mooring, loading and unloading.

While the end state of this development is highly uncertain and impossible to predict, is seems fairly certain that the coming years will see numerous developments in smart ships and autonomous vessels for specific applications (e.g. survey, inspection, crew change, waste removal). Some of the larger ports are already preparing for increased autonomy.

Big Data and artificial intelligence

Big Data is not just an amount of data too large for traditional data analysis, but rather a set of traditional (i.e. quantitative) data and non-traditional information from texts, images, social media and other such sources, enabling to achieve a certain goal that requires complex multi-parameter decision making. In the waterborne transport sector, this may for instance be route optimisation, fuel saving, emission reduction or waiting time reduction. Optimisation of an entire supply chain may also be such a goal.

One may qualify the data involved as high-volume, high-variety and high-speed, pointing at the large amount, the inhomogeneity and the speed at which the data need to be analysed (Figure 2.4). Note that it is not always possible or efficient to store all these data; sometimes they need to be analysed while streaming, saving only the results of the analysis.

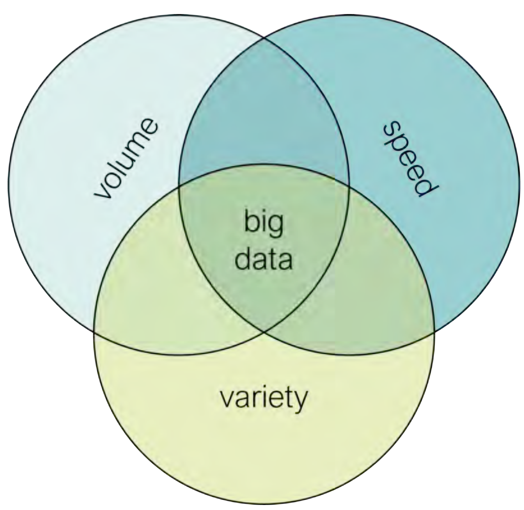


Figure 2.4: Characterisation of Big Data (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

DNV-GL, a worldwide operating registrar and classification organisation, identifies the following areas in which Big Data is expected to be of use in waterborne transport: technical operation and maintenance of vessels, energy efficiency, safety performance, management and monitoring of accidents and environmental risks from shipping traffic, and commercial operation and automation of ship operation (Mirovic et al., 2018).

Big Data offers special perspectives in combination with machine learning, an application of artificial intelligence. It aims at deriving predictive capability from the analysis of data, generally assuming these data to be homogeneous (i.e. free from large-scale trends). Hence, one might consider it as formalised experience, based on a large amount of observations. Machine learning in combination with Big Data can be of use in maritime transport for voyage planning, fuel saving, emission reduction, ship routing, safety, operational efficiency of ports and waterways, optimisation of supply chains, etc.

Producing such large amounts of data requires collaboration of many parties, in this case primarily ships and ports. This is why the Member States of the IMO have agreed that, as of March 2018, all ships larger than 5,000 gross tonnage have to share data on their consumption of all types of fuel oil, as well as some other relevant data, collected according to a uniform protocol. IMO collects these data in its Ship Fuel Oil Consumption Database, which is accessible to all Member States.

In inland waters the expected water depth is a key parameter, because it determines the allowable draught, hence the loading percentage of the vessels (Van Dorsser et al., 2020). Predictive capability of water depths is therefore of great importance for the optimal use of waterways. Especially in rivers, with their variable discharge and their morphologically active bed, this is not a trivial task. A novel development in this field is Covadem (https://www.covadem.org), a scheme in which depth data from on-board sensors of commercial vessels are shared, centrally stored, enriched with model predictions and made available to all participants.

With the advent of big data and machine learning, as well as the rapid developments in communication technology, such as 5G, it is fairly certain that data science techniques will strongly influence port and waterway engineering in the years to come. But where these techniques will be implemented first, and how that will affect all other processes in the supply chain, is still highly uncertain. Nonetheless, port and waterway engineers need to become skilled in data science methods, in order to be able to participate in this highly dynamic future.

2.1.2 Economic and political changes

Economies around the world go through cycles of rapid growth (boom) and stagnation (contraction) or decline (recession), superimposed on a long-term trend (Figure 2.5). These cycles translate directly into variations in trade and transport demand. As these cycles tend to occur at a timescale much shorter than the lifecycle of a port, port authorities and planners have to decide how they deal with them. Designing for the one extreme, the peak demand, is inefficient. Designing for the other extreme, however, implies long waiting times, causing loss of

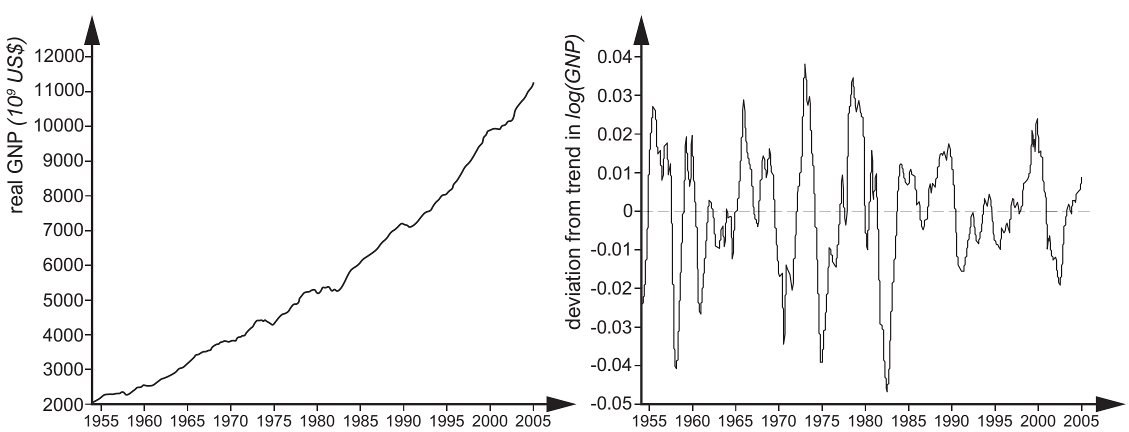


Figure 2.5: GNP-development in the USA between 1955 and 2005 (modified from Businesscycle figure1 and figure3 by Rochecon which are licenced under CC0 1.0, images by TU Delft – Ports and Waterways are licenced under CC BY-NC-SA 4.0).

service levels and reduced attractiveness. Where the optimum lies depends on local factors such as competition and hinterland.

Apart from these cycles, there may be changes in the global economic landscape, with upcoming and declining economies. Striking examples of the former are China and India, which have attracted large industrial complexes and the associated trade. At the moment, China has seven out of ten of the world's largest container ports (https://www.worldshipping.org – 2018). Consequently, at the other ends of the major transport routes large container ports are also needed, such as Rotterdam, Antwerp and Hamburg. It shows that, in order to profit from these worldwide economic developments, port planners need to understand how the global economic system works.

Changing economic relationships also occur at a regional scale. The EU, for instance, actively stimulates its new member states to come economically up to speed. This means that trade with these countries will increase, with obvious effects on international transport. Ports and waterways need to be ready to take on their share of this increasing demand. The opposite development may also occur, with the developments around Brexit as the most recent example.

Political decisions can have large economic consequences. Oil prices, for instance, are to a large extent politically determined, if not by the cartel of oil-producing countries, then by the threat of armed conflict between major states. An example of the impact of politics on the global transport system is related to the Suez Canal (see Section 1.1): its temporary blockades between 1967 and 1975, during the oil crises, led to the development of Very Large Crude Carriers (VLCCs) that are too large for the Canal and have now taken over a significant part of the worldwide transport of crude oil.

Also, customs barriers seem to revive as a political means to influence global trade. In recent years, interest rates are politically determined, due to the interference of the European Central Bank, for instance. The variation of such key parameters greatly influences the business case of a planned development. Their initiators therefore have to estimate how volatile or persistent these changes are, and therefore to what extent they need to be taken into account in their business case.

2.1.3 Changes in society

Society is not a constant factor in long-term decision making. Demographic changes like urbanisation may influence the availability of labour. Changes in consumption patterns, such as meat consumption, may influence the mix of transported goods. Increased drug abuse leads to more contraband, hence more severe cargo scanning and more delays in ports. Changing appreciation of environmental issues may lead to changes in legislation and environmental norms, hence in the possibilities for port expansion.

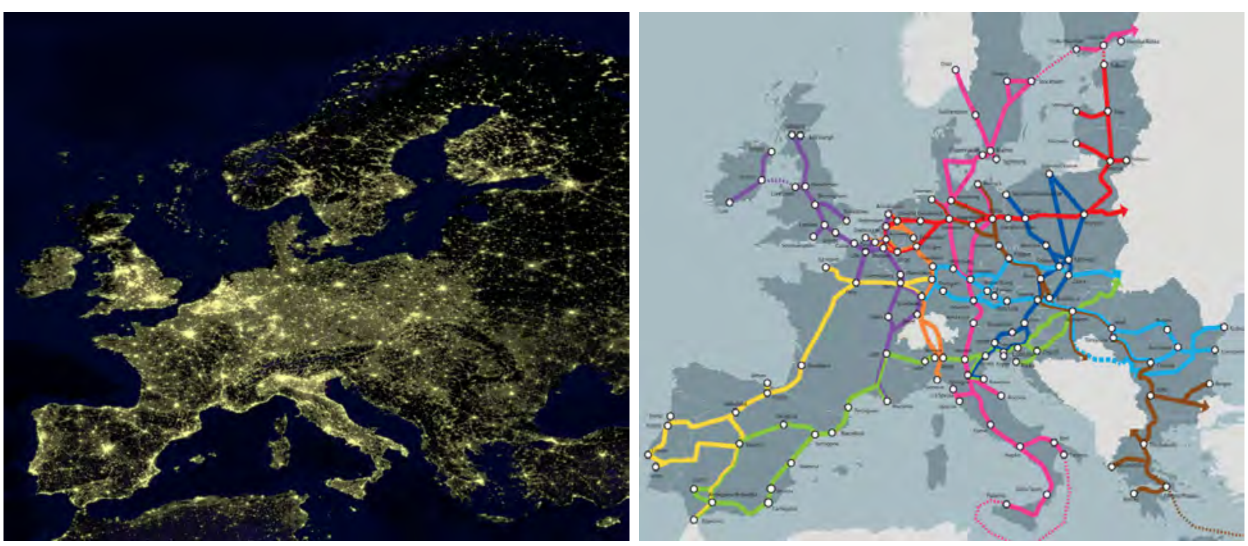


Figure 2.6: Population density and trade corridors. Left: Earthlights 2002 (by NASA is licenced under CC0 1.0); right: The Core Network Corridors (by European Union is licenced under CC BY 4.0).

On the other hand, trade routes and transport networks have influenced society since ancient times. People tend to settle where they can find a source of income and provision of goods. Despite the dramatically increased mobility of people, this is still the case at present. Urbanisation and megacity formation come with enhanced transport systems and they reinforce each other. Large concentrations of population are found around major transport corridors (Figure 2.6) and it is difficult to separate cause and effect.

In the meantime, citizens have become more articulate and know better how to use legal means to object against developments they don't want. The Port of Rotterdam experienced this when the first plans for the Maasvlakte 2 extension were rejected by the Supreme Administrative Court, because the environmental impacts were claimed to be insufficiently investigated. The way for port planners to go about this is not to ignore this kind of opposition, but to take it seriously and seek collaboration and compromises with all stakeholders in an early stage of development (see Part II – Section 1.3).

2.1.4 Climate change

The United Nations IPCC defines climate change as *"... a change in the state of the climate that can be identified (e.g. by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer"* (IPCC, 2007, Synthesis Report)). The IPCC has developed multiple models and scenarios that simulate the change of the atmosphere in the future. Emission scenarios, translated into CO_2-equivalents, are important drivers of these models. Nowadays IPCC uses four Representative Concentration Pathways (RCPs) (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) that represent the radiative forcing [W/m^2] of the atmosphere (Figure 2.7).

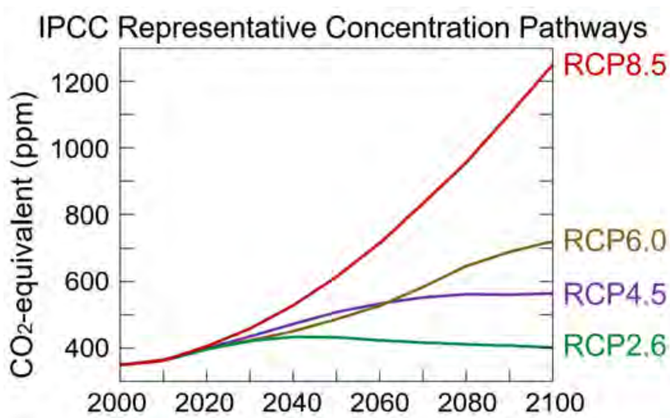


Figure 2.7: RCPs used in the Fifth IPCC Assessment Report (IPCC, 2014) (All forcing agents CO2 equivalent concentration by Efbrazil is licenced under CC BY-SA 4.0).

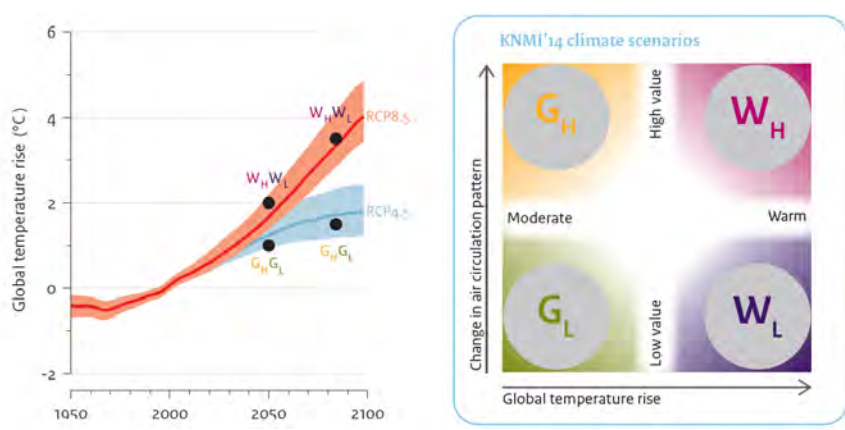


Figure 2.8: Climate scenarios (KNMI, 2014) (left: Global temperature rise according to IPCC (2013) is licenced under CC0 1.0; right: KNMI '14 scenarios is licenced under CC0 1.0).

For the Netherlands the IPCC-scenarios are translated for the Northwest-European region by the Royal Dutch Meteorological Institute (KNMI). It has defined four climate scenarios (G_L, G_H, W_L, W_H, see Figure 2.8) for the Netherlands that can be applied for the time horizons between 2050 and 2085 (flyer KNMI '14 climate scenarios, 2015 KNMI, 2015).

Impact on oceans, rivers and weather

The increase of the concentration of greenhouse gasses leads to global warming, of both the atmosphere and the oceans, and to changes in precipitation patterns. As a result of higher ocean temperature and melting of land-based ice sheets, the sea level will rise.

The melting of sea ice, especially around the North Pole, may have a quite different effect: the opening up of northerly navigation routes during a significant part of the year. This may lead to major changes in transport routes, for instance between Europe and Asia (see also Wikipedia: Arctic_shipping_routes).

There are no clear indications that there will be more storm activity on the Northwest-European coasts. As global water temperatures rise, there is an increased probability of Atlantic hurricanes bending northward (Haarsma et al., 2013), much like hurricane Sandy that hit New York in 2012. Such hurricanes can cause major damage to infrastructure on the coast, including port facilities. This may lead to not only significant repair costs, but also downtimes much longer than the storm's duration.

Climate change will also affect rivers, because they become more dependent on rainfall and groundwater seepage as mountain glaciers shrink. Hence the water inflow becomes more variable, which is aggravated by changes in precipitation patterns (longer droughts and more intense rainfall events). Hence discharge and water level variations are bound to become more extreme (Figure 2.9). Higher water levels during high flows give more downtime by lack of air draught under bridges, or more delays because bridges need to be opened. During extremes shipping

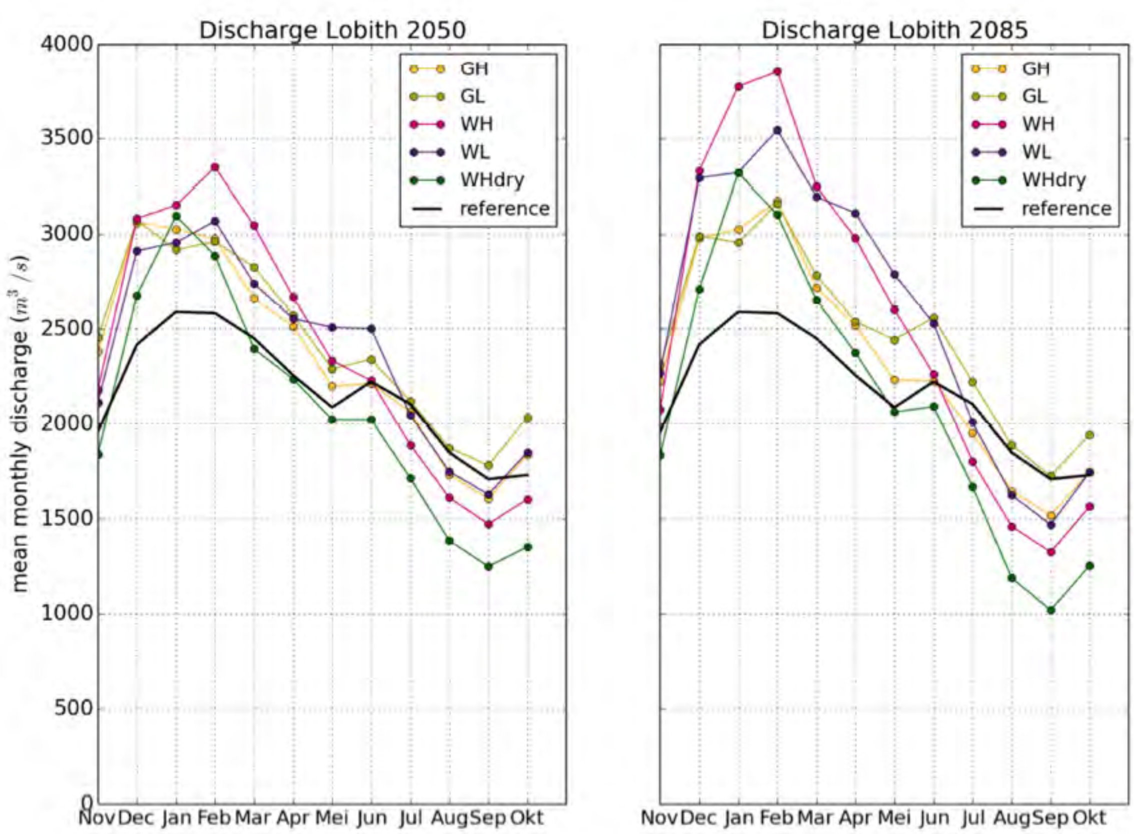


Figure 2.9: Monthly average Rhine discharges at Lobith for the different KNMI '14 climate scenarios (Sperna Weiland et al., 2015).

may be temporarily suspended to reduce pressure on dikes and levees at risk of overtopping/breaching. Low water levels during draughts reduce the load capacity of the vessels, hence to capacity of the waterway (Jonkeren, 2009; Van Dorsser, 2015; Van Dorsser et al., 2020). Here too restrictions may be imposed on shipping during extremes.

Without compensating measures, such effects clearly have implications for port operations and waterway capacity. PIANC-Envicom TG3 lists potential impacts and responses in its report Climate Change and Navigation (PIANC, 2008b). Many of them, however, are location-specific. Therefore, performance analyses of current supply chains have to reveal their vulnerability to climate change, as well as effective measures to prevent or mitigate them.

2.1.5 Accelerated relative sea level rise

Sea level has been rising throughout the Holocene, currently in the North-East Atlantic at a rate of about 0.20 m per century. In deltaic areas with a soft subsoil, this so-called eustatic sea level rise has to be combined with subsidence in order to calculate the change of sea level with respect to ground level. Subsidence can be due to tectonic effects (glacial rebound), the compaction of recently deposited sediments or peat oxidation. In the western part of the Netherlands, these subsidence effects add up to a multiple of the eustatic sea level rise.

Climate change is bound to accelerate eustatic sea level rise, at least on average, due to large-scale melting of land ice (Figure 2.10), though locally there can be deviations that are associated, for instance, with a changing mass distribution over the globe.

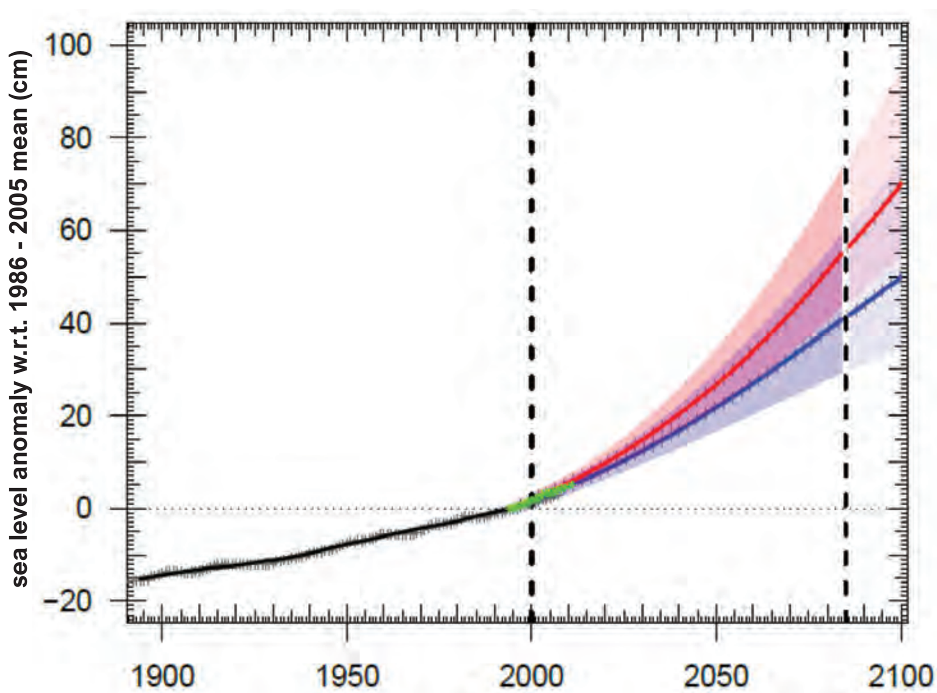


Figure 2.10: Eustatic sea level rise projections based on the KNMI '14 scenarios (modified from KNMI, 2014).

Relative sea level rise will have its impacts on coasts, ports and inland waterways. Coasts will exhibit a morphological response, generally erosive. This may also influence sediment transport patterns, possibly leading to increased port sedimentation. Inside the ports, structures need to be adapted to the higher water levels. It may also be necessary to take flood prevention measures for terminals and other port terrains.

The higher water levels, hence also the tide, will penetrate further into the rivers. Initially this will mean that fixed bridges need to be raised in order to maintain the fairway capacity. The increased tide also leads to erosion, but after some time this will be undone by sedimentation from upstream. The gain in navigable depth is therefore likely to be temporary. In the very long run, the effect of sea level rise is not restricted to the lower parts of the rivers, but will gradually extend upstream.

Adaptive and mitigating measures

To minimise the impact of climate change and relative sea level rise, a variety of adaptative or mitigating measures can be taken. Here we define the following main categories:

- port engineering measures (breakwater adaptation, flood protection measures, robust equipment, etc.);
- river engineering measures (detention areas, longitudinal groynes, floodplain measures, etc.);
- infrastructure adaptation (port water bodies, weirs and locks, bridge height, quay platform height, etc.);
- information management (water level forecasts, storm forecasts, Least Sounded Depth online, Covadem, route selection support, etc.);
- vessel technology (lighter materials, vessel design/dimensions, vessel trains, autonomous sailing, draught reduction devices, etc.); and
- logistic measures (hubs, synchro modality, stockpiling, 24/7 operations, etc.).

2.1.6 Ongoing human-induced changes

Apart from climate change and sea level rise, ongoing changes can occur in ambient conditions, for instance in response to events or interventions in the past. One example is the ongoing large-scale erosion of the Rhine branches, due to interventions such as the normalisations in the 19th and 20th century, sand mining and bend cut-offs. In large parts of the river this process is expected to continue in the next decades. As the water level follows the bed, structures of fixed height, such as lock thresholds or fixed bed layers, have to be adapted or built deeper than presently necessary. The former is the case, for instance, with the fixed outer bend layer near Nijmegen (Figure 2.11), the latter, for instance, with the new lock in the Twente Canal near Eefde, on the river IJssel.

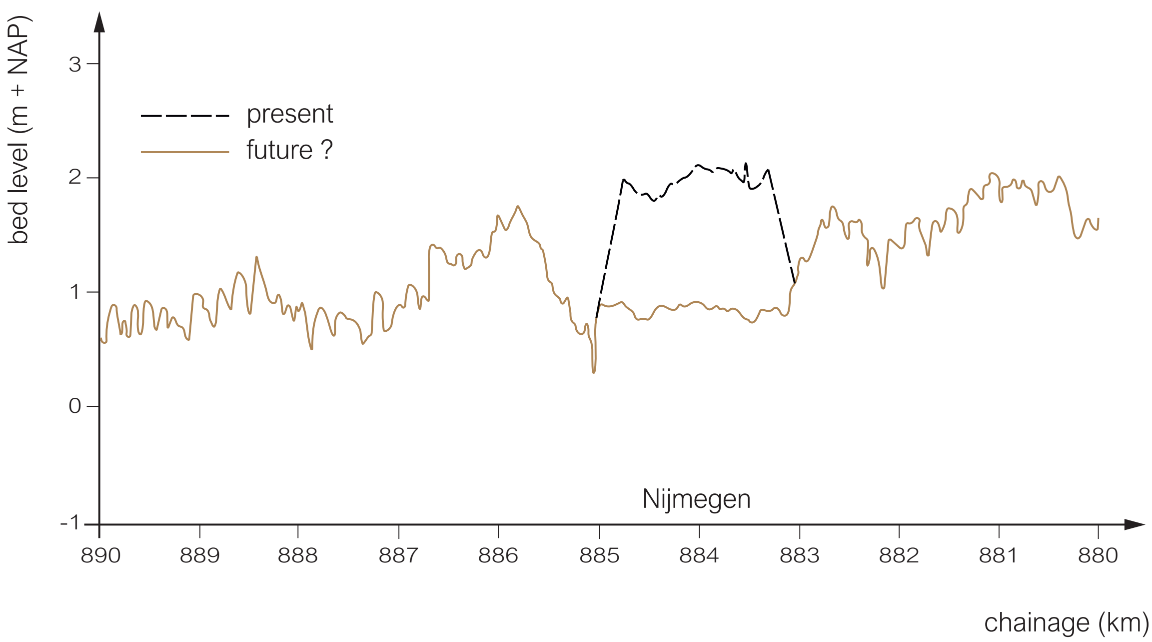


Figure 2.11: Fixed outer bend layer in the River Waal (built in 1988) sticks out of the eroding river bed and forms an obstacle to navigation (reworked from MIRT Onderzoek Duurzame Bodemligging Rijntakken, Rijksoverheid, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Another example of ongoing change is the Lower Ems (Tide Ems) upstream of Emden, Germany. Normalisation and deepening of the main channel to allow large cruise vessels to sail from the shipyard in Papenburg to the sea has led to an ever-increasing mud content in the river, up to environmentally unacceptable levels. Remediation requires expensive measures, leaving alone the question whether further deepening and widening for still larger vessels is an option.

Water and soil pollution can also exhibit long memory effects. If an area for port development is polluted, it should be remediated, otherwise the problem keeps coming back. Polluted water bottoms may keep leaching for a long time. Moreover, water quality problems outside the port, such as algal blooms, may penetrate into the port water bodies. Therefore, the recirculation times of these water bodies should be given due attention.

2.1.7 Crises and calamities

By definition, crises and calamities are unforeseen events with a large impact. Global economic crises may come to mind, but these are often stock-market crises which may be a forerunner of a recession. The response of trade and transport activities is generally not immediate or acute, so there is some time for adaptation. On the other hand, an economic low can last for several years, so it may certainly harm the transport system in the longer run.

Environmental crises can be more acute. Especially large events such as a calamitous release of poisonous matter or an accidental oil spill may lead to temporary closure of (parts of) a port to allow for remedial action.

In some cases calamities may be so detrimental that port operations are disrupted for a very long time. An example is the explosion, around 6:00 PM on August 2020, of 2.750 tons of ammonium nitrate which devastated the port of Beirut and a large part of the city. With port infrastructure and major storage facilities destroyed or severely damaged from the blast, all main supply chains into Lebanon were instantly disrupted. Since Lebanon relies nearly entirely on imports for all of its needs, this calamity impacted the country as a whole. Leading container lines immediately diverted ships to Lebanon's smaller port of Tripoli. Where Beirut's container terminal had an annual average capacity of just over 1 million TEU, Tripoli's has a capacity of 400,000 TEU. This could be enlarged to 600,000 TEU and a maximum of 750,000 TEU if more cranes are installed. Still, it would take a long time for all supply chains to be fully restored.

Futhermore, devastating earthquakes and tsunamis may bring down port activities for a longer time. Such events cannot be predicted accurately, but they can be prepared for, in areas where they are to be expected. This may save much trouble, costs and delays whenever they actually happen.

A special type of crisis is a large-scale health crisis. More or less regular examples are flu epidemics, which may temporarily reduce labour capacity. The 2020 Covid pandemic is a more extreme example for the transport sector, which has lasted longer and disrupted economic activities worldwide. This has financial consequences requiring robust financial buffers, but it also causes disorder in cargo throughput and supply chains, and may even bring long-lasting or permanent changes.

2.2 Planning port and waterway networks under conditions of uncertainty

When modifying existing waterborne transport networks, or developing new ones, the capacity to adapt to changes like the ones described in Section 2.1 should be taken into account. This requires knowledge of the waterborne transport system's functioning, as well as planning and design skills (technical, economic, legal). It also requires insight into the relevant trends, the uncertainties involved and ways to deal with these. In this chapter we lay a basic methodological groundwork for this. Part II – 'Ports and terminals' and Part III – 'Waterways' further elaborate the specific elements of the system and how to dimension these. Part IV – 'System performance' discusses how to analyse system performance.

2.2.1 The planning and design process

A transport network is a large-scale infrastructure that interferes at many points with spatial planning and environmental management. A port often covers a vast area which it excludes from other functions, and may have a significant environmental impact. A waterway cuts through an existing landscape and interferes with existing properties. It also crosses other infrastructural elements such as roads, railways, pipelines, cables or other waterways. Therefore, the development or adaptation of a transport network requires careful and time-consuming planning and design.

Suppose this has led to an overarching strategic goal at the political level, e.g. to stimulate the economy of an area, and that a first analysis reveals that this requires a better functioning transport network. Also suppose that the government has decided to enter the realisation process, what are the steps to be taken then?

Strategic Master Plan

The first step is a Strategic Master Plan (or pre-feasibility study), which includes explorative studies like:

- a global trade and transport analysis and the role the area may aspire to play;
- a problem analysis, focusing on what is lacking in the present transport infrastructure (e.g. a larger sea port, the ability to accommodate more types of cargo or better-functioning hinterland corridors);
- a solution outline (a new port, extension of an existing port with new terminals, satellite inland ports, capacity increase of certain fairways, etc.);
- economic considerations (may the benefits be expected to exceed the costs? What are the economic risks involved?);
- initial project definition (e.g. to extend an existing port with new terminals, to build a new sea lock for vessels of a certain size and with a certain capacity or to increase the navigable depth of a fairway);
- general functional requirements per project;
- planning implications (what to create where? How does this affect spatial planning? What are the environmental implications?);
- embedding in existing overall spatial plans.

This must lead to a Go/NoGo decision on a certain line of development, consisting of one or more projects to be further explored and elaborated.

Note that this process already has the character of a design process, in that iteration between steps may be necessary in order to achieve a solution that meets all requirements. It is also the phase where stakeholder involvement should begin, because this concerns the 'why' of the project(s).

Project Master Plan

Once the overall strategic Go-decision has been taken, a Project Master Plan is made for each of the projects to be realised. Part II - Chapter 2 describes such a plan for a port development. In general it includes:

- the strategic goal: what exactly one aims to achieve with the project;
- the relevant data (site conditions, cargo or traffic forecasts, vessel mix, etc.);
- specific functional requirements (service level, embedding in the network, etc.);
- a basic design, making it possible to investigate the project's feasibility;
- financial and economic feasibility studies, including a risk analysis;
- environmental aspects, not only in the form of an Environmental Impact Assessment (EIA), but also considering the possibilities of 'Building with Nature';
- social aspects, often in the form of a Social Impact Analysis (SIA), or a Societal Cost Benefit Analysis (SCBA);
- safety and security;
- management structure;
- type of contracting (construct-only, design and construct, design-finance-construct, design-construct-maintain, etc.).

This plan must provide sufficient information for a further Go/NoGo decision that sets the stage for permit procedures, financing arrangements, property acquisition, etc. A Go is also the start of the design process, which consists of the phases described below.

Functional design

The functional design translates the project requirements into one or more concrete objects that meet these requirements. Further below in this chapter we will give an example of how this works. Depending on the type of contracting, this design is made in-house by the project owner, by a hired consultant or by a contractor (often a contracting consortium). As port and waterway development usually involves large projects, the latter two options require a tender procedure.

Structural design

In this design phase the object is elaborated structurally, such that it is strong, rigid and stable enough under the design load conditions and can serve all its desired purposes. A quay structure, for instance, must be strong enough to carry the weight of the equipment and cargo on top of it, but also to resist the forces exerted on it by a moored vessel. Moreover, its foundation has to be stable enough to prevent subsidence and its earth-retaining structure has to be rigid enough not to give way to the soil-mechanical forces exerted on it.

Execution design

Designing an infrastructural object is one thing, constructing it is another. The realisation of a complex object like a port, terminal, lock or waterway is a complicated operation that requires careful planning in space and time. It encompasses timely ordering, delivery and storage of material and components, organisation of construction activities, management of subcontractors, safety and security, reduction of interference with other activities and infrastructures, etc. In this phase the last permits may have to be arranged. In case of large projects with a high exposure, a special point of attention is public communication (publicity, visitors, logging, etc.).

Operation and maintenance

Once the object has been realised, it is handed over to the user. Clearly, enabling optimal operation is a design requirement. Sooner or later, however, maintenance will be needed. Facilitating this (in order to reduce costs and downtime) increasingly receives attention in the design phase.

2.2.2 The 'Frame of Reference' approach to design

The basic template

Planning and design, as described in the previous subsection, is an iterative process that people use to achieve certain objectives. A systematic approach to this is the Frame of Reference (FoR) approach developed by Van Koningsveld and Mulder (2004) (see also Laboyrie et al., 2018). It works with a set of closely interconnected elements that need to be specified in any planning and design process (see Figure 2.12).

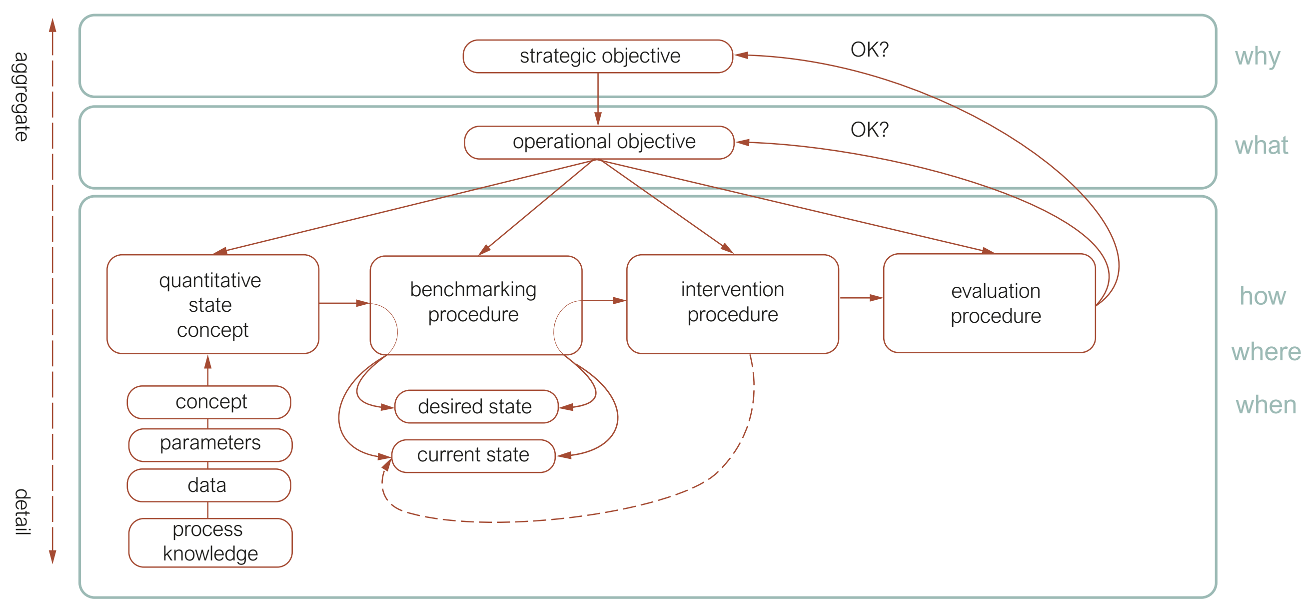


Figure 2.12: Basic 'Frame of Reference' template (reworked from Marchand, 2010, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

It starts with the definition of clear objectives at strategic (why?) and operational (what?) levels. When the objectives are clear a practical decision recipe should be designed, specifying how, where and when the objectives will be met. The decision recipe involves specification of the following elements:

- a Quantitative State Concept (QSC),
- a benchmarking procedure,
- an intervention procedure, and
- an evaluation procedure.

The **strategic objective** indicates 'why' the planning and design process is needed in the first place. It often specifies an overarching larger-scale longer-term goal, such as the ambition to develop an efficient and sustainable transport network.

The **operational objective** specifies 'what' will be undertaken specifically to achieve this overarching goal; more or less like the program requirements of a construction project. In the case of a lock design, for instance, it indicates what the capacity of the lock should be, under what conditions it has to function, what environmental constraints have to be respected, what the cost limit is, etc.

The **Quantitative State Concept (QSC)** specifies how important aspects of the operational objective will be quantified, i.e. related to transport capacity, environmental impact, operating cost et cetera. As such the QSC forms the explicit link between the operational objective and the benchmarking procedure that indicates whether or not intervention is required to achieve that objective.

In the **benchmarking procedure** the current (or predicted) state of the system is compared with its desired state; both expressed in terms of the QSC. Any discrepancy is an indicator of a problem, and as such a trigger for intervention.

We should point out that we define 'indicators' as assemblages of QSCs that indicate whether or not there is a problem. This implies the need for comparison with a reference or benchmark. Often the word, indicator, is used for things that should actually be considered parameters, values or system properties. Here we reserve the word, indicator, specifically for usage in a problem-solving context: the indicator must indicate if there is a problem.

The **intervention procedure** should (iteratively) produce an intervention of such dimensions that the problematic current (or predicted) state is converted to an acceptable state. This may sound trivial, but in practice is often not explicitly demonstrated.

In the **evaluation procedure** the performance of the decision recipe is evaluated against the operational *and* the strategic objectives. This two-level evaluation procedure may give rise to reformulations of the objectives, a different QSC, a different reference state or a different intervention procedure.

It is furthermore important to specify which authority is assumed to be responsible for the implementation of the resulting FoR, as this may affect the specification of solution elements.

Ideally, all elements of the basic FoR template are made explicit in the end user-specialist interaction. Remaining 'white spots' represent information gaps for decision making and may become part of a knowledge agenda.

The FoR approach has been applied to a variety of projects, in which specialists from different disciplines, nationalities and backgrounds engaged with policy- and decision-makers. It has been used (implicitly) since the 1990s in the Netherlands for the successful development and implementation of a scale-resolving coastal sediment management policy (Van Koningsveld and Mulder, 2004; Mulder et al., 2011). It was also used in various European research programmes, for example in the CoastView project, where the Argus video observation system, among others, was employed in the management of dynamic navigation channels (Medina et al., 2007). Laboyrie et al. (2018) recently proposed to use the FoR approach as tool for project assessment.

In this book we apply the FoR approach to port and waterway problems. Examples of where the FoR approach could be of use are:

- *Functional design of a lock* – To maintain the transport capacity of a waterborne transport network in an efficient manner (strategic objective), it may be decided that waiting times should not exceed 30 minutes (operational objective). A QSC that describes the total passing time of a vessel (including time spent waiting) could be used in an iterative design process where lock dimensions are varied until the 'modelled' waiting time, for the design traffic intensity, is smaller than the maximum allowable waiting time of 30 minutes (benchmarking/intervention procedure). The evaluation would show that the operational objective is achieved (waiting times < 30 min), but a closer look might reveal that high costs are incurred for a rarely occurring situation, or that mooring line forces exceed safe limits. This could trigger a round of sharpening the objectives, modifying the QSC, changing the intervention procedure, et cetera.

- *Functional design of a container terminal* – To competitively handle a certain throughput of TEU (strategic objective), it may be decided that average waiting times should not exceed 10% of the average service times (operational objective). A QSC that derives berth occupancy from a predicted vessel mix and call size and a selected crane capacity and number of cranes, could be used in an iterative design process where quays and cranes are added until the 'modelled' waiting time as a factor of service time is smaller than the maximum allowable 10% (benchmarking/intervention procedure). The evaluation would show that the operational objective is achieved ($\overline{WT}/\overline{ST} < 10\%$), but a closer look might reveal that the calculated quay and crane configuration is not very robust for future changes, or that other elements of the terminal now become bottlenecks. This could trigger a round of sharpening the objectives, modifying the QSC, changing the intervention procedure, et cetera.

Obviously many other examples can be conceived. In Part II – Part IV information is provided that should enable you to develop complete FoRs for a wide range of port and waterway related design challenges and perform first-order quantification.

2.2.3 The 'supply chain' concept

The previous subsection described the FoR approach as a systematic procedure to develop designs. A pivotal element in the basic FoR template is the QSC, as it creates an explicit link between the operational objective and the benchmarking procedure. A useful concept in the analysis of waterborne supply chains is the supply chain concept, which we briefly introduced in Chapter 1 as the multi-stage connection between the supplier of a good and the receiving customer (Figure 2.13). Supply chain analysis helps to give insight into how a transport system functions and interconnects, whether it performs as desired and what are potential measures for improvement.

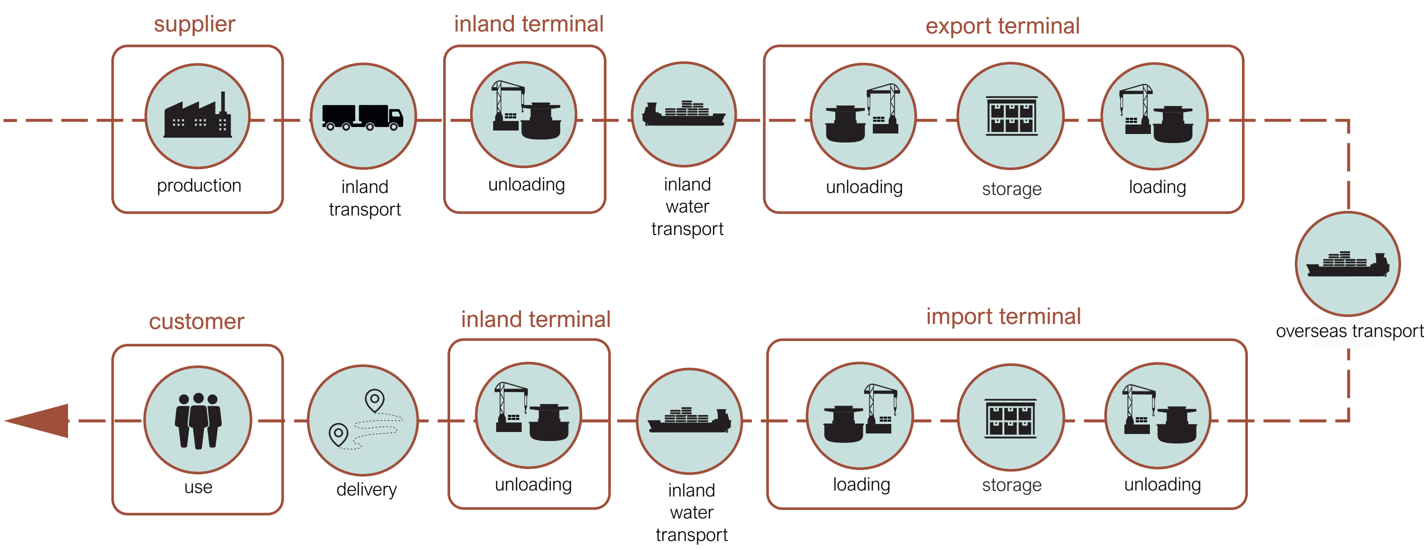


Figure 2.13: Supply chain as the link between supplier and customer (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The chain concept also applies at a more detailed level to many of the elements of this overall supply chain. The functioning of an import terminal, for instance, can be mapped onto such a chain model (Figure 2.14). Clearly, this chain can also be reversed in the case of export.

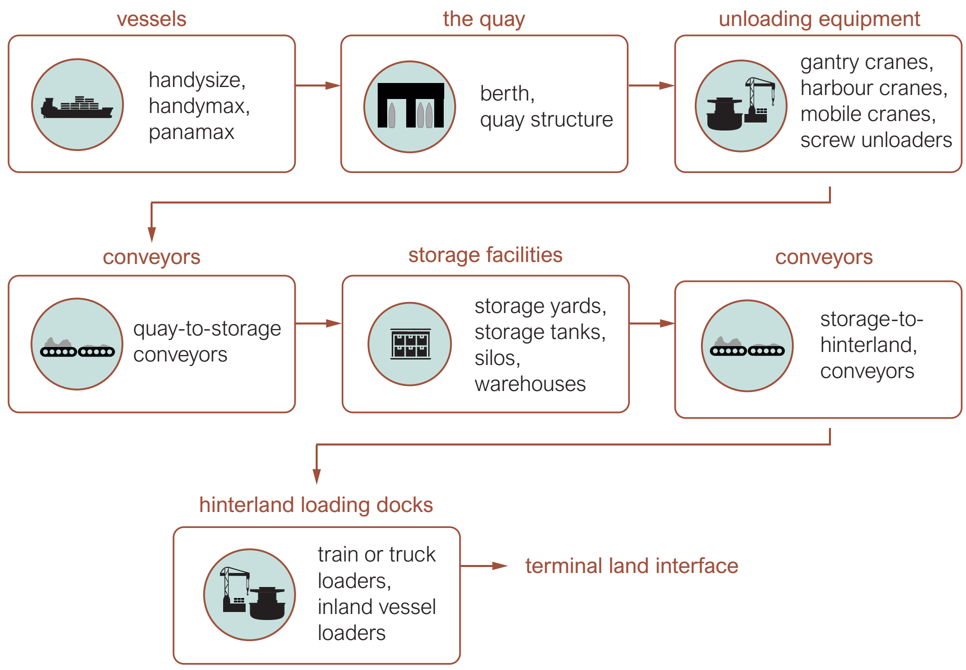


Figure 2.14: Chain model of a dry bulk terminal structure (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Other parts of the overall supply chain can also be represented by a chain model, as shown in Figure 2.15 for inland transport.

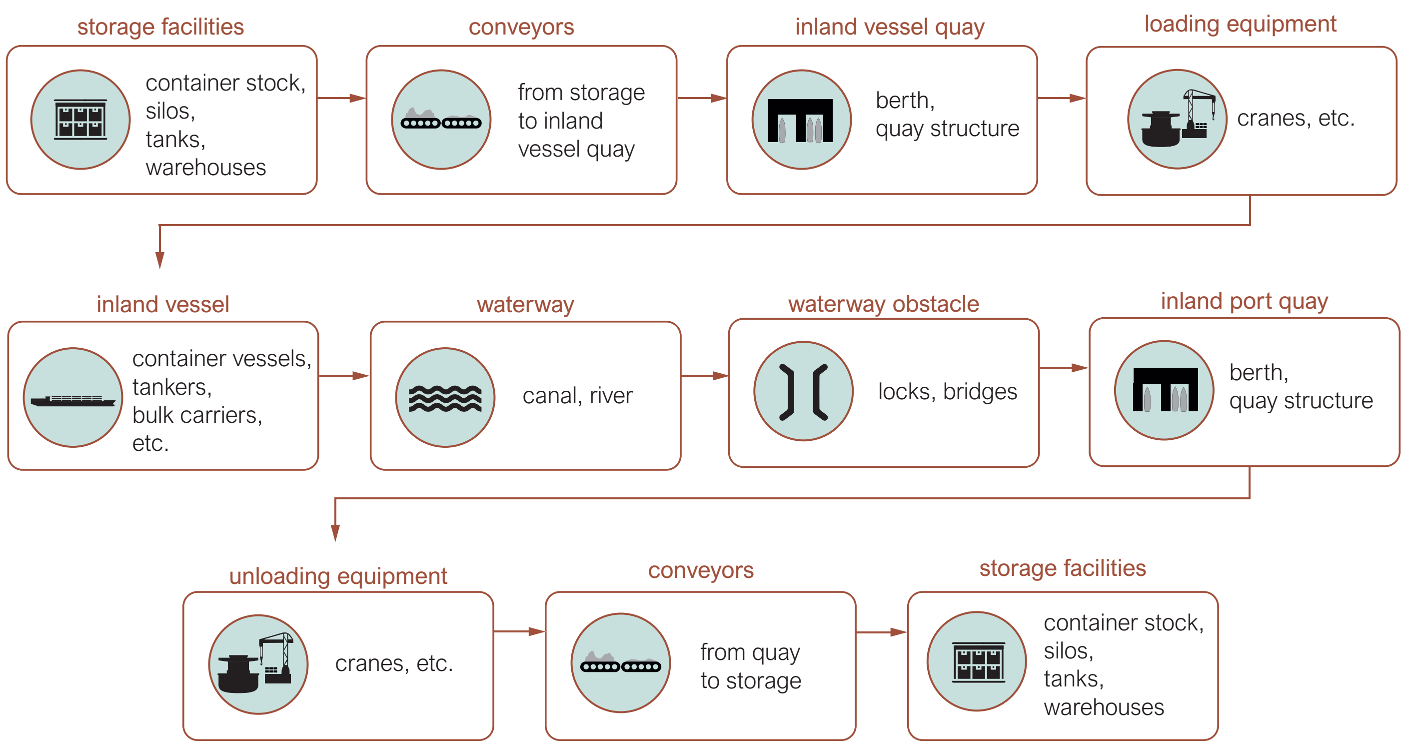


Figure 2.15: Chain model of inland waterway transport facilities (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Note that Figure 2.13, Figure 2.14 and Figure 2.15 suggest a linear process. The interactions, however, are mutual, with multiple feedback effects. If congestion occurs at a certain point in the chain, for instance, 'upstream' actors may decide to temporarily change their operations, or to move over to another transport modality. Furthermore, other chains may link in or split off, for instance in case of multiple suppliers in different parts of the world, or multiple customers at different locations.

By considering a terminal as a chain of interlinked elements, and terminal operations as a coherent set of activities that move cargo through this chain, it is possible to calculate handling times, queue formation and throughput estimates, and to identify bottlenecks that limit these throughputs. Hence the 'supply chain'-concept forms a basis for balancing and optimising the terminal design (at master plan level as well as at functional design level). Implemented in simulation software it can help establishing how best to respond to changing conditions, such as a throughput increase that exceeds the existing capacity, or a change in vessel mix that no longer fits the existing quay structure. It also enables risk analysis at system level and the establishment of redundancy requirements in case one or more elements underperform or fail. Finally, it provides the basis for economic analysis.

Considering the inland transport network as a chain of interlinked elements and inland shipping as a coherent set of activities that move cargo through this chain provides similar opportunities for analysis, optimisation and adaptation. Applying this concept to both terminals and waterways allows us to connect them to form waterborne transport systems.

2.2.4 Financial aspects and investment decisions

The previous subsections discussed the process of planning and design, the use of the 'Frame of Reference' to approach this systematically, and the supply chain concept as a means to analyse system performance and to develop and assess the effectiveness of alternative measures. A next step is to investigate the feasibility of the alternatives. A key aspect to decide on feasibility is how costs and benefits are balanced. It is good to realise that there is a big difference in the way private organisations and public entities come to a decision.

Private financing or ownership

The role of private parties in the financing of infrastructure can be twofold. One possibility is that a private financier makes capital available against a certain annual rate of return without being involved in the operation. A Cost-Benefit Analysis (CBA) of the project can be performed to estimate the risk, hence to establish the rate of return that is required. In such an analysis incoming (+) and outgoing (-) cash flows are compared, to check if the net result is positive. The second possibility is private ownership, where the private party finances the infrastructure and has it built, operated and maintained. Such parties also decide to invest on the basis of a CBA.

Outgoing cash flows to be taken into account are:

- the costs of invested capital (opportunity costs of own as well as borrowed capital),
- the CAPital EXpenditures (CAPEX), to produce non-consumables such as built structures, but also to acquire land, for instance;
- the OPerational EXpenditures (OPEX), associated with running the infrastructure, such as labour cost, energy cost, insurance, etc.
- the costs of maintenance (yearly maintenance costs are usually included in OPEX),
- renovation and/or replacement costs requiring new capital, and
- the costs of decommissioning.

Furthermore, there may be exhaust emission costs in each development step.

Revenues are mainly operational, e.g. from port dues and tolls if the investing actor is a port authority, or from product sales if the investing actor is a terminal operator. The overall business case should account for the residual value that is represented by the assets at the end of the projected lifecycle.

The aforementioned costs and revenues materialise at different points in time, as Figure 2.16 shows. It is important to note that these timing aspects can be very important for the overall business case.

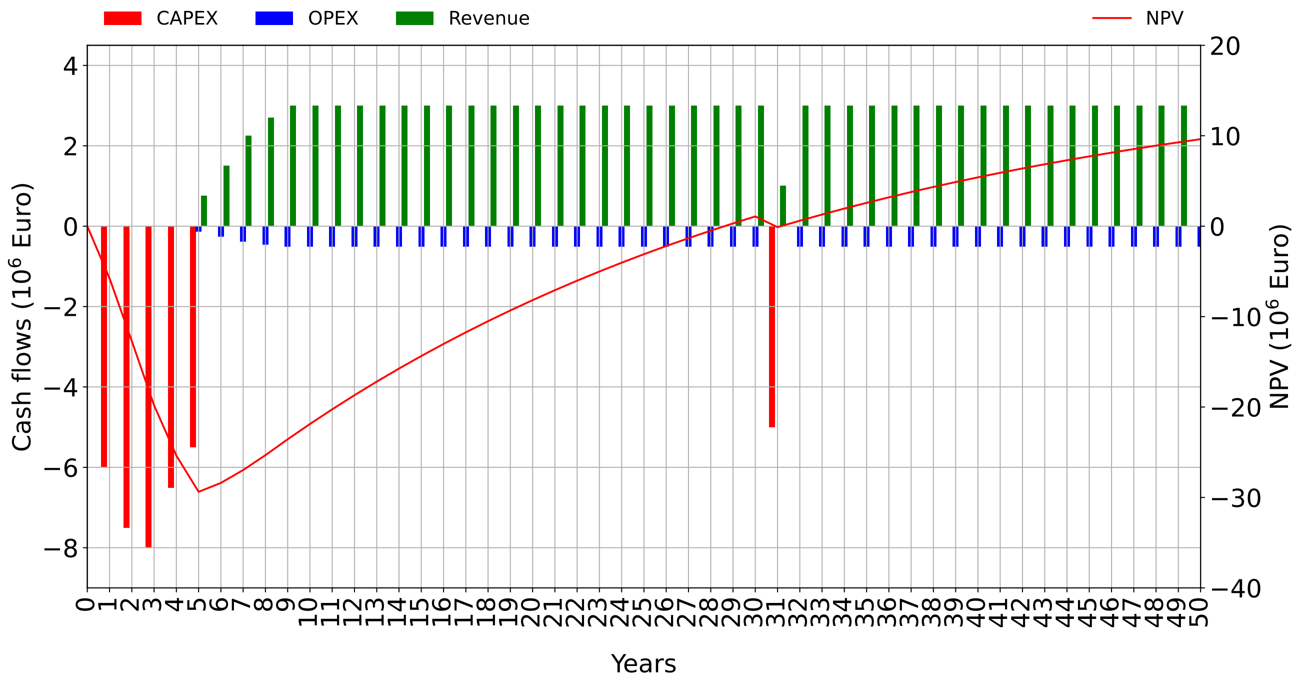


Figure 2.16: Hypothetical example of the time-distribution of expenditures and revenues, with a capital-demanding renovation after 30 years (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The Time Value of Money (TVM) concept implies that an amount of money spent or earned now is worth more than that same amount in the future. This is based on the assumption that money can earn interest. To take the TVM concept into account, all cash flows are translated to one point in time, to arrive at the Present Value (PV). This can be done by a process named discounting. Assume that if an investor can have an annual rate of return on capital of r percent on average, then he will expect a similar revenue from an investment in an infrastructural project infrastructure. The same goes for own capital: if it would be invested elsewhere, it would produce an annual rate of return r percent on average, so if it is invested in the project it may be expected to produce the same return. From the point of view of the project, these are cost items, named opportunity costs of the invested capital.

In order to cover the opportunity costs, the invested capital C_0 has to grow every year by a factor $(1+r)$. So after n years it has become:

$$C_n = C_0(1+r)^n \tag{2.1}$$

assuming the rate of return r to be constant over time. The other way around, the present value of C_n follows from:

$$C_0 = C_n(1+r)^{-n} \tag{2.2}$$

So, the further into the future, the smaller the present value of capital.

If we apply Equation 2.2 to the yearly Net Cash Flow (NCF), the total Net Present Value (NPV) for years 0 to n becomes

$$NPV_n = \sum_{k=0}^{n} \frac{NCF_k}{(1+r)^k} \tag{2.3}$$

in which r is called the discount rate. If a project has a positive NPV over its life cycle, it is financially feasible.

Yet, this is not the whole story. If one considers the nominal value of capital, a monetary unit (Euro, Dollar, etc.) in the future is the same as that unit now. But the real value, i.e. amount of goods one can buy for that unit, changes over time due to inflation. So if an investor requires a real rate of return of r' percent, the discount rate has to be corrected for inflation. Assuming a constant inflation rate i and following the same rationale as above, the real value of the invested capital grows in one year by a factor $(1+r)/(1+i)$, in which r is the nominal discount rate. This means that after n years it has become:

$$C_{nr} = C_0 \left(\frac{1+r}{1+i}\right)^n \tag{2.4}$$

and the present value of an amount C_{nr} now follows from:

$$C_0 = C_{nr} \left(\frac{1+r}{1+i}\right)^{-n} \tag{2.5}$$

This means that the discount rate corrected for inflation follows from:

$$r' = \frac{1+r}{1+i} - 1 \tag{2.6}$$

In summary, inflation implies that the nominal capital should accrue more in order to compensate for the loss of real value, and that the discount rate should therefore be smaller.

Apart from the NPV, other useful financial metrics are:

- the Internal Rate of Return (IRR), which is the discount rate that yields an NPV of exactly zero,
- the Benefit Cost Ratio (BCR), i.e. the ratio of the revenues over the expenditures (CAPEX + OPEX), all expressed in present values, and
- the discounted payback period, i.e. the time needed for the cumulative PV of the revenues to exceeded the cumulative PV of the expenditures (the break-even point).

In the Netherlands, a fixed discount rate for public projects is set by the government. In other cases, it depends on the market for capital, which is often rather volatile. The sensitivity of the investment decision to the ensuing uncertainty can be estimated by evaluating the NPV for various discount rates. In general it can be stated that business cases will improve if outgoing cash flows (costs) are reduced and postponed, and incoming cash flows (revenues) are increased and brought forward.

The NPV analysis described above implicitly assumes that capital investments, once committed, stay as they are. Since the future is uncertain, it may be necessary at some point in time for the project management to adapt to changing conditions, with additional financing needs and implications for the project's further prospects. Techniques such as Real Options Value (ROV) allow us to take flexibility into account in the initial financial assessment.

Publicly owned infrastructure

Government decisions are less driven by financial return on investment than by the consequences for the welfare and well-being of society as a whole. Nevertheless, the government is expected to underpin its decisions with facts and figures. Therefore, such decisions are supported by another evaluation tool, the SCBA. In principle, this tool can be used to evaluate alternatives in the funnelling process of a master plan (see Part II – Section 2.1). The complexity of large infrastructure projects, however, with many stakeholders and affected interests, a long life cycle with many uncertainties, and costs and benefits falling to different parties, makes the application of SCBA rather complex and laborious. Therefore, its application is often limited to comparing the preferred alternative with the null-alternative, so as to underpin a Go/NoGo for the project.

An SCBA systematically maps out all relevant societal and environmental effects of a project, if necessary based on preceding impact analyses specifically made for this project. As far as possible, these effects are quantified and expressed in mutually comparable monetary terms (PVs), leading to a balance of costs and benefits for these effects. By doing the same for the null scenario, avoided costs and missed benefits can also be taken into account.

Not all effects can be monetised on the basis of market prices. Techniques such as risk assessment and ecosystem service assessment can help to valuate these aspects so that they still can be taken into consideration (see also Laboyrie et al., 2018). Yet, some relevant effects will remain that cannot be expressed in monetary terms and still have to be made visible in the SCBA. In view of the often complex and laborious nature of a full SCBA, simpler forms have been developed. In order of increasing complexity:

- *Quick Scan* – gives a first indication of the most important effects and related costs and benefits on the basis of substantiated assumptions and experience from similar projects.
- *Index-based CBA* – similar to a full SCBA, but effects, costs and benefits are estimated on the basis of generally applicable index values derived from other studies.

Public-private partnership

There are many forms of Public-Private Partnerships (PPPs), from joint financing, via joint realisation through to joint operation and maintenance of projects. Correspondingly, there are many contract forms, in which the distribution of costs, benefits and risks among the partners is an important issue. In project realisation arrangements the government generally focuses on the final goal of the project and does not interfere with the realisation process. This is different than the traditional way of working, where the government and its consultants produce a complete design, which is executed as such by the contractor. In PPP arrangements, the government focuses on achieving the ultimate goal, which gives the private parties room to optimise the realisation process.

Examples of such integrated contract arrangements are:

- *Design and Construct (D&C)* – where the contractor, often assisted by consultants, develops and builds the design and subsequently hands it over to the client. This enables optimal tuning of design and execution. Many of the projects of the Room for the River program in the Netherlands have been realised under this type of contract. Maasvlakte 2, the recent extension of the port of Rotterdam, was also realised under a D&C-contract.
- *Design, Construct, Maintain (DCM)* – where the contractor guarantees the proper functioning of the object during a set period of time. This stimulates maintenance-friendly designs. An example is the new City Bridge across the river Waal at Nijmegen.
- *Design, Build, Finance, Maintain (DBFM)* – where the contractor also arranges the project's financing. Examples of DBFM-projects in the Netherlands are the second lock in the Twente Canal near Eefde and the new sea lock in the North Sea Canal at IJmuiden.
- *Design, Build, Maintain, Operate (DBMO)* – where during a specified period of time the contractor is also responsible for the operation and maintenance of the project. This enables further optimisation.
- *Design, Build, Finance, Maintain and Operate (DBFMO)* – this is at present the most extensive form of integrated contracting.

2.2.5 Natural and social environmental aspects

Apart from financial feasibility, which is typically driven by supply chain optimisation and investments in capacity and efficiency (cost and benefits), an intervention's overall feasibility also depends on environmental aspects. Natural as well as social environmental aspects (negative or positive) need to be considered carefully whenever designing port and waterway solutions. Some aspects can be monetized and may be incorporated into the investment analysis. Other aspects, however, may be hard to monetize but can be influential nonetheless.

Ports, waterways and the activities they support are bound to have environmental effects. Not only by the space they occupy, but also by producing emissions, noise, light, dust, odour, waste, water, air and ground pollution, dredging, (contaminated) dredged material management and the like. The transport of hazardous goods may lead to risks for public and natural environment.

The increasing public awareness of environmental issues drives interest groups and administrations to demand reduction of adverse environmental footprints. It has led to national and international legislation and conventions concerning various types of environmental impacts. Examples of the former are the European Union (EU) Framework Directives. Examples of the latter are the International Convention for the Prevention of Pollution from Ships (MARPOL), a global convention initiated by the IMO, and the regional Convention for the Protection of the Marine Environment in the North-East Atlantic (OSPAR).

Meeting these demands and the range of environmental legislation requires a change in attitude of authorities and decision makers, towards a proactive approach of the environment, public access to relevant information, participative decision making and fair cost allocation (see also Laboyrie et al., 2018).

When developing and operating ports and/or waterways, due attention must be paid to important environmental policy issues, such as:

- decision making based on balanced environmental, social and economic considerations,
- protection, conservation, restoration of nature values,
- mitigation and compensation of (residual) environmental effects, and
- seizing opportunities to cleverly combine infrastructure development and operation with nature enhancement (e.g. Building with Nature (BwN), Engineering with Nature (EwN) and Working with Nature (WwN)).

In most countries, port development requires Environmental and Social Impact Analysis (ESIA), embedding in existing spatial plans and compensation or mitigation of negative impacts. In Part II of this book we describe how these fit into the port planning process. Here we briefly discuss some environmental aspects, associated with ports and waterways, that deserve special attention:

Accidents Waterway operations and IWT involve risks. Shipping accidents may lead to blockage of the fairway and vessels having to make long detours in order to reach their destination (Figure 2.17), resulting in time loss, extra energy consumption and extra emissions. The accidental blockage of the Suez Canal of March 2021 is a prime example of an accident with implications at global scale. Accidents may also lead to spills and hazardous situations with dangerous cargo (explosions, chemical gas releases) involving fatality risks or public health risks. Port and waterways planners should take the probability of accidents into account, and consider alternative options they need to make available should an accident actually occur.

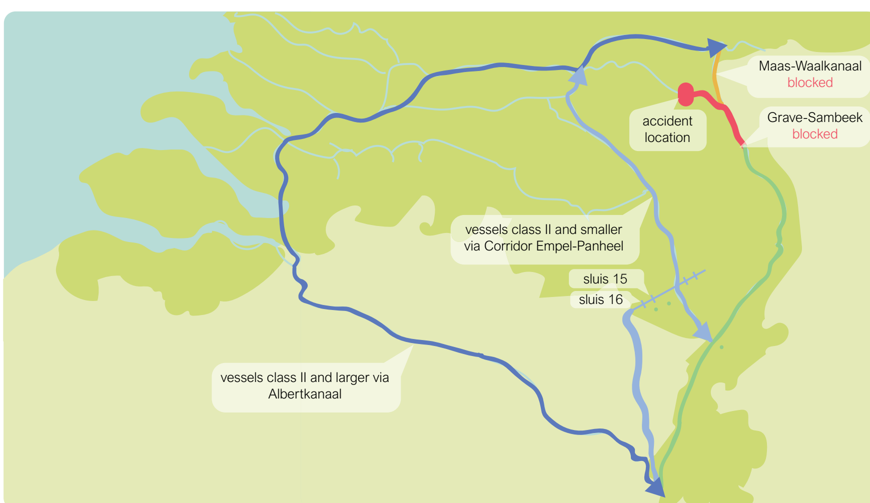


Figure 2.17: Detours required after a shipping accident at the weir of Grave (red circle) (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Dangerous cargo A determining factor for the risk involved in handling dangerous cargo in ports is the location. A risk analysis can produce risk contours (Figure 2.18), such that in the design of the port layout one can make sure that sensitive areas stay outside contours with unacceptable risk levels.

Figure 2.18: Individual fatality risk contours for an oil terminal, Port Botany, Australia (background: Spatial Service State of New South Wales, contours: Sherpa consulting, image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Important risk-reducing measures are

- structural measures (buffer areas, containment systems, firefighting facilities, safe storage),
- information (when will how much of this type of cargo be in the port?),
- operational measures (regulations, communication, safety measures), and
- contingency and emergency plans and corresponding facilities.

RVW (2020) (see Part III – Chapter 5) also refers to risk contours along waterways. Within a certain contour (e.g. individual fatality risk 10^{-6}) no buildings are allowed. Information provision, operational measures and contingency and emergency planning also apply to waterways.

Dredging and dredged material management Dredging is common in most ports and waterways, to create channels or port water bodies (capital dredging), to remove deposited sediment (maintenance dredging), or to remove contaminated sediment (environmental dredging). Apart from consuming energy and emitting greenhouse gases, dredging disrupts the benthic system, causes turbidity, and produces dredged material (see also Becker et al., 2015; Laboyrie et al., 2018). Turbidity plumes can be carried with the current to environmentally sensitive

Figure 2.19: Dredging activity in the Fehmarnbelt, Germany ("Fehmarnbelt Fixed Link Dredging and Reclamation, 2021" by Royal Van Oord is licenced under CC BY-NC-SA 4.0).

places, where they may do harm by extinguishing light and depositing sediment. Within ports the currents are generally weak, but nevertheless plumes may spread (Figure 2.19), for instance due to wind-driven currents, tidal filling and emptying and density effects. In rivers and coastal zones currents, and hence turbidity spreading, are obviously stronger. In rivers groyne fields and other sheltered zones cause additional dispersion, because turbidity lingers there. Research efforts have long been focused on reducing the source (hopper overflow) or containing the turbidity where it does less harm, using screens or bubble screens, for instance (Figure 2.20). Recent research also focuses on reducing the impact on the ecosystem, for instance by careful timing of dredging operations and the re-use of dredged materials (Laboyrie et al., 2018).

Figure 2.20: Dredging-induced turbidity containment with a bubble screen (Turbidity & Dredging by Royal Van Oord is licenced under CC BY-NC-SA 4.0).

What to do with the dredged material depends on its properties. Clean sand can be used in the building industry, or for coastal nourishments, landfills or land reclamation. Within a few years dewatering of unpolluted mud yields clay (Van Eekelen and Bouw, 2020), which can be used for dike building, for instance. Unpolluted clayey material with a sufficient organic content can also be used for wetland restoration. Slightly polluted material can be placed at designated locations, away from the dredging location at sea, for instance. The biggest problem is the heavily polluted material, which needs to be decontaminated prior to re-use or disposal, or stored isolated from the environment. An example of such a storage area is the Slufter near Rotterdam (Figure 2.21).

Figure 2.21: The Slufter storage basin for polluted sediment (yellow box) (Sentinel-2 cloudless 2020 by EOX IT Services GmbH is licenced under CC BY-NC-SA 4.0).

Dust, noise and light Especially the handling of dry bulk cargo, such as grain, coal, china clay and metallic ores, produces dust. Strong winds may also entrain fine particles from stockpiles. Furthermore, soot and ash are produced by ship engines burning fuel oil. These ship engines, however, also emit sulphur and nitrogen oxides, which can react in the air to dust. Prevailing winds may spread this dust over adjacent residential areas. Especially fine dust (particle size less than 10 μm) is a threat to public health. The present EU-limit of 20 $\mu g/m^3$ for air pollutant concentrates is rather demanding for many a port.

Dust production by cargo handling can be reduced by spraying, covering during transport, using vapour return systems when stocking, and careful profiling of stockpiles. Careful port layout planning, taking into account residential areas and the prevailing wind direction, is a prerequisite. Fine dust production by sulphur and nitrate emissions can be reduced by changing to other fuels for seagoing vessels. The IMO is trying to achieve this by compulsory information provision on the use of heavy fuel oil and by imposing sulphur oxide limits per ship (see Section 2.1.1). Another emission product that causes environmental problems is nitrate, which acts as a fertiliser in nature areas and thus threatens biodiversity. Although port operations and inland water transport are not the main sources, this requires attention. Especially in the vicinity of intensively used waterways, such as the river Waal, the contribution can be significant (Bloemen et al., 2006).

Noise and light produced by port activities and port-related traffic can be significant nuisances for people living nearby, sometimes even a health risk. The port layout, with elements like green areas and cleverly positioned service buildings, can help sheltering residential areas from such noise and light. An EIA generally requires noise level contours, including scheduling of noise activities to occur at times of the day that cause least effect for receptors.

Waste Waterborne transport systems inevitably produce waste. This can be waste from ships (sewage, household waste, bilge water, oily water from engine operations, ballast water), from industry, offices, warehouses, dwellings and other facilities. Ports are supposed to have reception facilities and usually organise waste reception in such a way that it does not cause unduly delays to the vessels. Hazardous waste (as explicitly defined in EU-directive 2008/98/EC on waste) has to be stored in a well-isolated and well-controlled landfill. Storage and treatment of waste are generally significant cost items, so they should be taken into account in the port's economic analysis, as well as in its design.

A kind of waste that deserves special attention from an environmental perspective is ballast water. If natural water is taken in and discharged elsewhere in the world, it may introduce invasive species that may disturb the local ecosystem. A possible temporary measure is to exchange ballast water mid-ocean, but it is better to either take in treated water, or treat it while the ship is on the way to its destination. In 2017 the IMO Ballast Water Management Convention came into force. It requires 'all ships in international traffic to manage their ballast water and sediments to a certain standard, according to a ship-specific ballast water management plan'.

Water and soil pollution Important causes of water and soil contamination around ports and waterways are (illegal) disposal, leakage, spills and accidents. Industrial and tank storage areas in ports, for instance, can be sources of serious contamination if they are not properly isolated from the surrounding water and subsoil. Even if isolation measures are currently in place, there is often a legacy from the past.

Prevention is the best strategy, as remediation is usually quite expensive, if possible at all. Depending on the environmental risk it constitutes, contaminated soil can be isolated, or the contamination can be immobilised otherwise. If contaminated water is released into the groundwater, one may attempt to contain the plume. Oil spills on confined water, such as a port basin, can be removed will oil beams, since oil floats on water and mixes poorly with it. The port must have protocols and facilities ready to combat this kind of events. If an oil spill occurs at open sea, removal is much more difficult, because wind and currents spread the oil slick quickly. This can lead to environmental disasters, like the 1989 Exxon Valdez disaster in Prince William Sound, Alaska (Figure 2.22).

Soluble contaminants entering surface water will soon disperse and become difficult to remove or contain. There can also be diffuse sources, such as leaching from old soil contaminations. One example is eutrophication by fertilisers leaching from former agricultural land. This may lead to harmful algal blooms, also within port water bodies. The remedy is regular recirculation of the port water, for instance by flushing.

Figure 2.22: The Exxon Valdez oil spill disaster, Alaska, 1989 (left: OilCleanupAfterValdezSpill by NOAA is licenced under CC0 1.0; right: EVOSWEB 013 oiled bird3 by Wikimedia commons is licenced under CC0 1.0).

A special kind of pollutant originates from some types of antifouling on ship hulls. Fouling is the formation of a layer of micro-organisms and larger species (e.g. mussels, barnacles, seaweed) on the submerged part of the hull. It causes extra resistance and influences the manoeuvring properties of the ship. Moreover, ships with fouled hulls spread the organisms all over the world, thus causing problems with invasive species. In the seventies and eighties of the last century an environmentally very harmful type of anti-fouling paint was used. Since then, more environmentally-friendly alternatives have been developed.

Habitat Ports cover large areas from which a variety of species may have been driven off. Canals intersect habitats, thus blocking the exchange of terrestrial species and cutting predator territories. Fluvial waterways have often required river regulation, at the expense of habitat variation in the river bed. Estuaries, being links between ocean and inland waters, are favourite places for port development, but also places where one can find the biologically most productive wetlands (worldwide loss of these wetlands stands at 35-40% since 1970; see Ramsar Convention on Wetlands, 2018).

Such environmental impacts generally require compensation. International conventions, such as the Ramsar Convention for Wetlands, see to this. Regional regulations like the EU Framework Directives and Natura 2000 formulate environmental protection objectives and force countries to develop and enforce compliant legislation.

The impact of port and waterway activities on sensitive habitats can be minimised by taking proper mitigation measures, determined by the local conditions (environmental, social, legislative). In general, it is most environmentally friendly and cost-effective to prevent loss of habitats by minimizing the footprint of activities, rather than to lose and restore them. If impact cannot be avoided, restoration is often required by an EIA or societal pressure. Before carrying out habitat restoration, an in-depth analysis is needed of the physical, ecological and societal boundary conditions to select the most suitable and cost-effective method. Following the restoration activities, monitoring is critical to document the status and development of the restored habitats over time.

Although scientists have been discussing ecosystem services and ecosystem valuation for decades, this concept has found broader acceptance only recently (see also Laboyrie et al., 2018). It provides a method to quantify the effects of an envisaged development on the ecosystem in monetary terms and include them in an SCBA.

Ecosystem services are generally grouped into four broad categories (MA, 2005):

- *supporting services* – such as nutrient cycling, primary production, soil formation, habitat provision and pollination,
- *provisioning services* – such as the production of food, raw materials, energy and medicinal resources,
- *regulating services* – such as carbon sequestration, climate regulation, waste decomposition, water purification and flood protection,
- *cultural services* – such as spiritual, recreational, scientific, educational and therapeutic.

Valuing these in monetary terms requires subcategories. One of the methods to do so is contingent valuation, based on public inquiries into the 'willingness to pay' for certain ecosystem services.

2.3 Adaptive planning

The previous section outlined basic steps that need to be considered when planning port and waterway networks under conditions of uncertainty. We should realise that these steps can be completed under different paradigms, all of which acknowledge the prevalent uncertainty and try to manage it.

2.3.1 Uncertainty and increasing complexity

Planning of infrastructure involves various timescales, such as the:

- *planning horizon* – the time period for which the plan is made;
- *technical lifetime* – the time during which a structure or equipment is expected to keep on functioning technically;
- *economic lifetime* – the time during which structures and equipment fulfil the system's functional requirements;
- *depreciation time* – the time during which the carrying amount of the infrastructure is reduced to zero; and
- *trigger timescales* – the timescales at which the various triggers of change take place.

These timescales are not mutually independent and tend to become shorter now that market, technology and circumstances change more rapidly. As this shortening is not uniform over the various timescales, their mutual relationships may change, which increases complexity.

In the past, transport infrastructure was built to provide the same service for a long time. The technical lifetime of civil engineering infrastructure, for instance, is typically 50 years or more. This used to be of the same order of magnitude as the planning horizon and the economic lifetime. At present, 50 years is way beyond the latter timescales. This means that the concept of a single functionality throughout the technical lifetime has to be abandoned, or that one should opt for a shorter technical lifetime. But this is not the only complicating factor in present-day infrastructure planning for waterborne transport. Uncertain future developments (see Section 2.1) further complicate the challenges of port and waterway planning.

2.3.2 Towards a new paradigm

The traditional way of dealing with uncertainty and complexity is to reduce uncertainties to a level at which they can be ignored or captured in safety margins. Now that changes become faster, more unpredictable and more extreme, this paradigm is no longer good enough: we have to accept risk and uncertainties and deal with them explicitly and systematically. In management literature, this is referred to as decision making under Volatile, Uncertain, Complex and Ambiguous (VUCA) circumstances (see Barber, 1992); the US Army War College is attributed for introducing the term VUCA. This new paradigm is referred to as 'Adaptive Planning' (see Taneja, 2013).

Risk and uncertainties not only create vulnerabilities, they also provide opportunities. The challenge is to seize the opportunities and hedge or reduce the vulnerabilities. This can be achieved by incorporating flexibility (the ability to be modified if and when needed) and robustness (the ability to withstand or overcome adverse conditions) in the system, whether it is a port, a port network or a supply chain. As far as uncertain events or developments can be specified, one may devise measures to deal with them and implement them when needed. Clearly, uncertain events or developments which we are not even aware of at present can only be faced with robustness and hedging.

Measures providing flexibility to real systems and projects are known as Real Options. They can be incorporated in physical infrastructure, in operations or in services. These Options can be exercised in case of changed functional requirements. We will illustrate this by a number of examples.

In the 1990s, when major investments in container terminals were being made at the Maasvlakte (Port of Rotterdam), fourth-generation ships with a draught of 12.5 m were current. Yet, the container terminals at the Europahaven and Amazonehaven were provided (at extra cost) with deeper draughts and higher quays which could accommodate heavier cranes, so as to accommodate the larger ships that might call at the port in the future. As ship size continued to grow, this flexible Option has enabled berthing much larger vessels (starting with an 11,000 TEU container ship in 2008) (Taneja, 2013). In Part IV – Section 3.2 we describe how such an extra investment can be justified by estimating the added value of a flexible Option in a business case.

Another Rotterdam-based example is the phased construction of Maasvlakte 2, which gave the port authority the option to abandon or defer the following phase of the project and avoid part of the capital expenditure in case the market deteriorated (Taneja, 2013).

The unprecedented growth of container transport forced some ports to adapt their bulk terminal to handle containers (cf. Part II – Figure 1.5). Ports that did not adequately respond (adapt, expand, resettle) were forced out of business. Presently, as hydrogen is being touted as the fuel of the future, investigations into adapting existing LNG terminals are in progress worldwide.

As these examples illustrate: flexibility offers advantages during uncertain times, as ports can be adapted for new or changed use, thereby also promoting sustainability by way of efficient use of resources. This does not mean, however, that investments in flexibility are always taken into consideration. The focus on short-term profits, the lack of a long-term perspective in planning, and the lack of tools to value flexibility are deterrents to such investments.

2.3.3 Adaptive Port Planning

The planning of capital-intensive systems with a long lifetime needs to account for uncertainty and incorporation of flexibility and robustness during the planning process. Adaptive Port Planning (APP) is an integrated planning method that guides planners to systematically deal with uncertainties that appear over the lifetime of a port. It allows for change, learning and adaptation over time, based on new knowledge and changing circumstances.

APP recognizes that the value of a project (or a design alternative) is driven by the flexibility and robustness it needs, in order to survive in the uncertain and rapidly-changing world. Therefore, identifying, evaluating, incorporating and managing Real Options is an important step in APP. APP results in a robust, flexible and adaptive plan that stands a good chance to perform well no matter what the future brings (Taneja, 2013).

The next steps are the implementation of this plan, implementation or preparation of the measures and the development and implementation of a monitoring plan that must identify early signals of relevant change, thus triggering activation of the contingency plan. Table 2.1 compares the traditional and adaptive planning approaches.

Aspect	**Traditional planning approach**	**Adaptive planning approach**
Attitude towards the future	Assumes it is useful and possible to predict the future	Assumes the future cannot be predicted, or it is risky to do so
Treatment of uncertainties	Uncertainty is included in the scenarios, but planning is eventually based on single-point forecasts	Imagines trend-breaks and events and prepares for them
Planning process	Static and instantaneous, or at most periodic	Dynamic and continuous
Focus	Demand forecasts	Vulnerabilities and opportunities
Approach	Target-oriented	Performance-oriented (hence flexible, robust and integrated)
Reactivity	Ad hoc to strong signals (certain knowledge of the future)	Monitoring and responding to predefined triggers (mostly performance indicators)
Decision making	Based on available information	Based on regular acquisition of new information and evaluating potential developments as a way to deal with uncertainty

Table 2.1: Comparison of planning approaches (Taneja, 2013).

Figure 2.23 presents a schematic of the adaptive planning process (after Taneja, 2013). The result of this process is the preferred basic plan plus a set of pro-active measures to deal with uncertainties and a contingency plan.

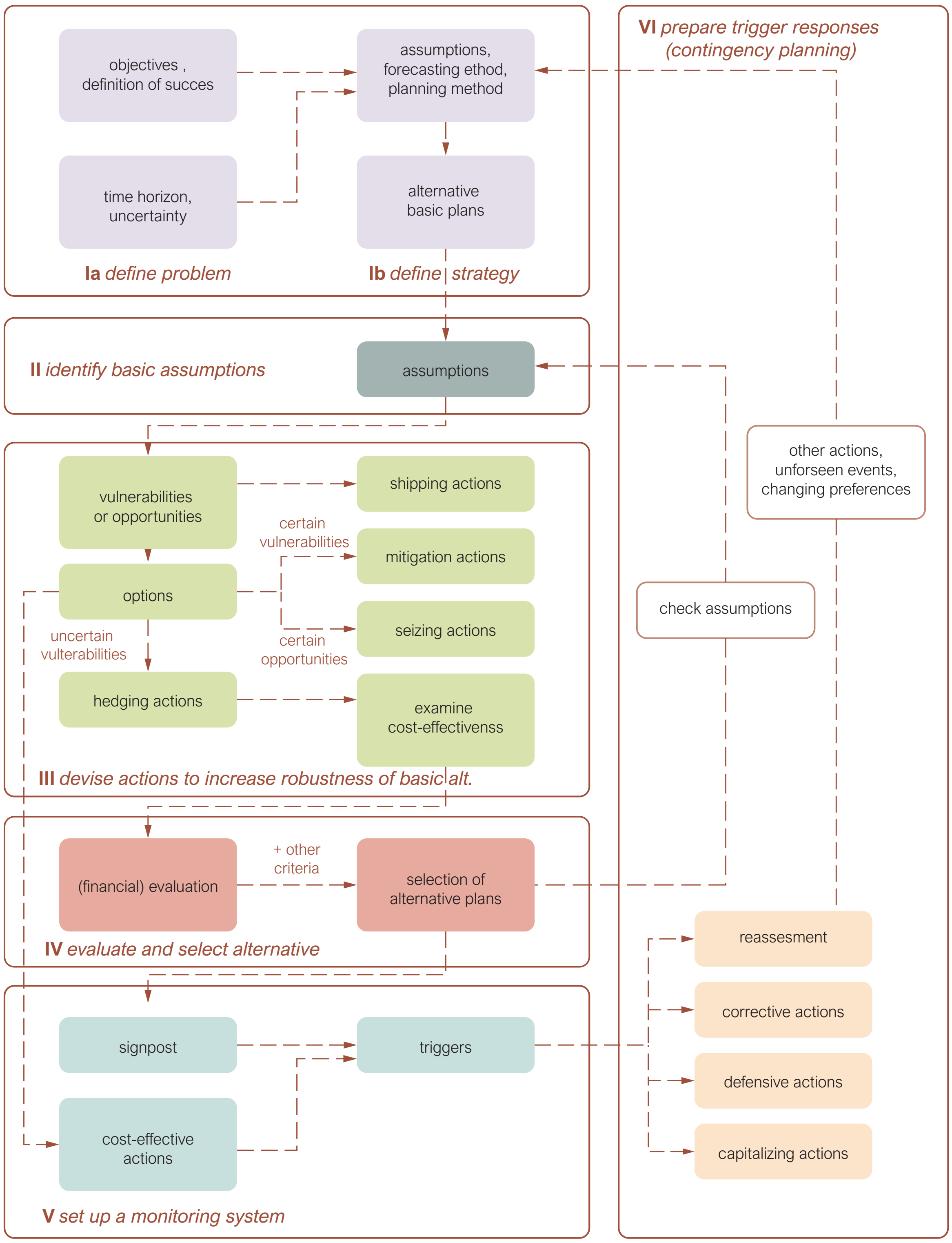


Figure 2.23: Framework for Adaptive Port Planning (reworked from Taneja, 2013, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

3 Connecting with the next parts

The previous chapters provide a concise introduction into the topic of ports and waterways. They show that waterborne supply chains are of worldwide importance, carrying approximately 90% of global trade. These supply chains, and the transport networks they rely on, form an intricate coherent system: changes to one element are likely to affect other elements in the system, where impacts have the potential to range from small and temporary to global and permanent. These systems furthermore operate in a rapidly changing and highly competitive world, which means that flexibility and adaptivity are a matter of survival.

Port and waterways engineers engage with this complexity to develop and compare alternative strategies for the design and operation of waterborne supply chains, and their supporting networks, in support of decision making. This requires capabilities to:

- *execute performance analyses* – with respect to pre-defined objectives for capacity, efficiency, safety and sustainability;
- *develop functional designs* – in terms of required system elements and their order-of-magnitude dimensions;
- *perform feasibility studies* – quantifying costs and benefits of alternative measures, embedding the design into the social and natural environment; and
- *quantify important aspects of these analyses* – using rules of thumb, calculation methods or simulation models, to support discussions between stakeholders and decision makers with transparent and objective information.

In support of the above we introduced the 'Frame of Reference' approach as a systematic way of thinking in terms of objectives and the extent to which alternative measures contribute to their achievement. We proposed the 'supply chain'-concept as a structuring and unifying method to analyse system performance and to suggest improvements. Furthermore, we observed that the systematic quantification of incoming and outgoing cash flows, while considering the Time Value of Money (TVM) and well as the difference between nominal and real values, is a good approach to investigate a solution's financial feasibility. Natural and social environmental considerations also play an important role. Finally, the concept of 'Adaptive Planning' was introduced as a method to account for the many uncertainties that surround the development of port and waterways systems.

Based on this general introduction in Part I, more detailed information, needed to actually execute calculations, is provided in the three following parts:

Part II addresses **Ports and terminals**. It highlights their importance as nodes in waterborne transport networks, and discusses important aspects that should be considered carefully while developing port master plans and port layouts. As a next level of detail, within the overall port layout, we discuss the dimensioning of individual terminals. As an example, we elaborate key aspects of container supply chains and provide a basic guideline enabling readers to develop a functional terminal design, specifying the required terminal elements and their order-of-magnitude dimensions, for a given design throughput. Other terminal types are treated briefly, highlighting specifics to consider when designing each one.

Part III deals with the connections between the nodes of waterborne transport networks: **Waterways**. After discussing the importance of transport over water, it provides guidelines for the functional design of waterways and waterway elements, such as locks and bridges. Special attention is given to the ship-induced water motions as they effect ship-waterway and ship-ship interactions. Finally, traffic management systems are discussed.

Where Part II and Part III deal with ports and terminals and waterways respectively, Part IV focusses on **System performance** and gives examples of ways to quantify important aspects of ports and terminals, waterways and port and waterway systems. It makes ample reference to available simulation tools, some developed at TU Delft, that help to quantify the analyses, and make the results explorable and communicable.

We believe that this structure, and the content provided, helps current and future engineers to become valuable contributors to the interesting and important field of port and waterway engineering.

Part II

Ports and terminals

1 Challenges to port development

Part I gives a general introduction to ports and waterways and describes their function in supporting waterborne supply chains. Part II addresses ports and terminals in more detail. Before addressing port planning (Chapter 2), port layout (Chapter 3) and the functional design of terminals (Chapter 4 and Chapter 5), this chapter gives a basic introduction into the challenges of port development.

1.1 Historic importance of ports

Since ancient times, ports have played an important role in societies. They brought trade, wealth, contact with other societies and (military) power.

In ancient Egypt, long before the port of Alexandria was established, the port of Canopus on the west bank of the westernmost Nile branch enabled grain export from the fertile Nile basin, mainly to Greece. In about 1900 BCE the port of Alexandria (Figure 1.1) took over (although the city of Alexandria did not yet exist by the time) and continued grain export, first to Greece, later to Rome and Constantinople. An interesting observation reported by Strabo (64 BCE – 24 CE) is that the local inland port on Lake Mareotis (Figure 1.1) was busier than the sea port. Apparently, Inland Water Transport (IWT) also occurred in ancient Egypt.

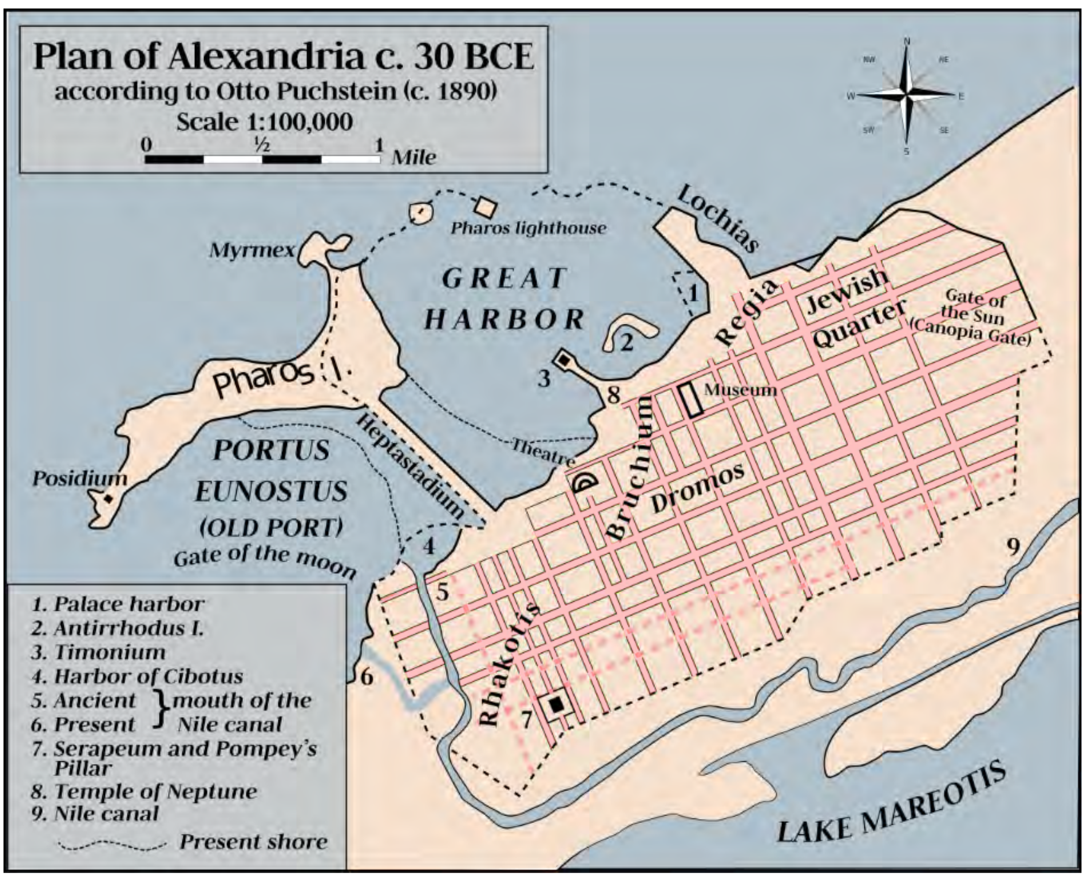


Figure 1.1: The ancient port of Alexandria (by Philg88 is licenced under CC BY-SA 3.0).

Around 400 BCE the city of Athens created a military and commercial port at Piraeus. It has played a key role in the establishment of Greek power in the Mediterranean (Lambert, 2018), and at the same time became a trade centre for a wide variety of goods. From 300 BCE Rome had its port at Ostia Antica, on the mouth of the river Tiber, first only commercial, later also military.

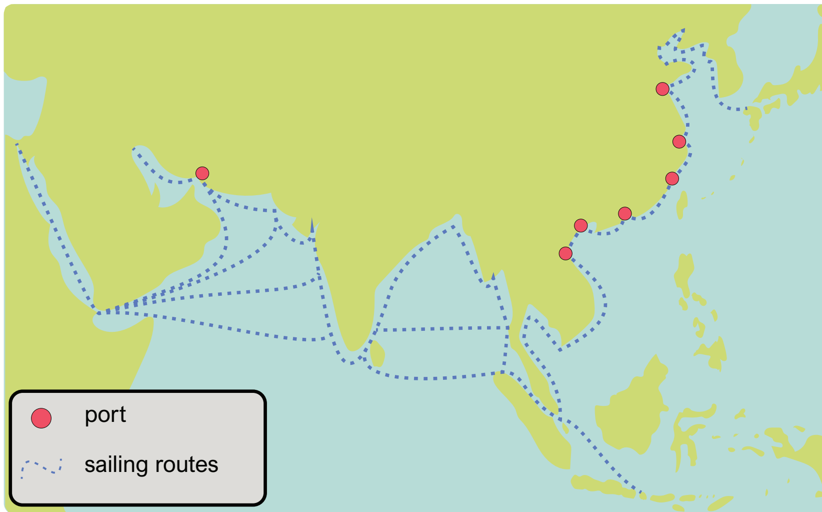


Figure 1.2: The "Silk Road on the Sea" (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

In China the port of Guangzhou, established during the Qin Dynasty (221 – 206 BCE), served for many centuries (till around 1500 CE) as a node of the "Silk Road on the Sea", a trade route which extended from Korea, all along the Asian coasts, to Africa and Europe (Figure 1.2).

Later on, between the years 1000 and 1500 CE, the port of Venice became a leading European port, which was instrumental in developing trade in the Mediterranean and beyond. The city of Venice thrived along with the port and became a prominent centre of power and culture in Southern Europe.

Another, more recent example is the spectacular development of Singapore (see Figure 1.3) since its independence in 1965, the success of which is attributed to its port. In the old days it was a hub for European and Chinese merchants, and now one of the world's biggest ports, which attracts foreign companies and functions as an international centre for maritime-related business and commercial services.

Figure 1.3: The port of Singapore, left: around 1900 (Port in Singapore by Lambert & Co., G.R. / Singapore is licenced under CC0 1.0); right: at present (Bestand:Keppel Container Terminal, Singapore by Noel Reynolds is licenced under CC BY 2.0).

The influence of sea trade and ports on economic development has grown and developed through the centuries. In fact, ports and cities (and the countries around them) have always developed in a self-reinforcing relationship, where growth in port activity led to economic growth and vice versa.

The above examples illustrate the mutual interaction between cities and their ports. While ports profit from knowledge and business services concentrated within the city, the port is a source of employment and global commercial and cultural contacts for the city.

Today, the growth and economic prosperity of many cities around the world, such as Barcelona, New York, London, Hong Kong, Hamburg or Antwerp, can be attributed to shipping and ports. The Netherlands, for instance, have been able to sustain a relatively high economic growth rate because of the Port of Rotterdam, which in the 15th century used to be just a fishing port. In China, the export-driven industries have enabled small fishing towns to turn into the world's largest metropolitan regions and biggest ports, and China's economy into one of the fastest growing in the world.

On the other hand, ports are part of a closely-knit network of actors and facilities that keeps the worldwide supply chains going. In order to function optimally, all elements have to stay sharply tuned to each other, while the world is constantly changing: new players step in, new technologies emerge, demands change, transport facilities evolve, transport corridors develop, worldwide economic relations change, the balance of political power shifts, a disruptive pandemic breaks out, et cetera.

An example of how this system can get (temporarily) destabilised is the disruption of the oil supply chain, due to the Corona-pandemic 2020-2021. Oil production has a certain inertia, either physical (shale oil production), or political (Saudi-Arabia vs. Russia, OPEC). So a sudden collapse of the market means a large temporary overproduction, a sharply increasing demand for storage capacity and tumbling oil prices. In 2020 this even led to negative prices for crude oil. A port may temporarily profit from this by selling its excess storage capacity, but in the longer run it will suffer from the reduced trade.

Getting out of tune with the other elements in the supply chain goes at the expense of a port's efficiency and maybe even its service level and reputation. On the other hand, a timely response to changes may enable a port to strengthen its position and maybe even outcompete nearby competitors. The large investments involved make this a game of high stakes and high risks, which explains the importance of sensible and well-informed port planning and development.

1.2 Port development

1.2.1 Generations of ports

As illustrated above, development of ports is a continuously ongoing process, rather than an incident at the start of their lifecycle. In the period after World War II, globally a number of distinct stages of port development have been identified, often referred to as 'generations' (e.g. UNCTAD, 1999):

- *1st generation* – Until about the 1960s, the services of a port were limited to transporting goods between land and sea through a local or regional hinterland.
- *2nd generation* – As processing industries were installed in the vicinity of the ports, they became transport hubs and centres of industrial and commercial activity.
- *3rd generation* – After the 1980s the development of containerised transport accelerated and international networks of intermodal connections along with it. In response, ports extended their services with value-added logistics.
- *4th generation* – Fourth-generation ports carry out core, value-added and industrial activities, but are also nodes in a network of ports/terminals supporting supply chains and port-city interactions, and focus on a wider ecosystem and a sustainable existence.

In the literature there is even mention of fifth- and sixth-generation ports (e.g. Lee and Lam, 2016).

1.2.2 External changes

Game changers affect the development of ports worldwide abruptly. Ongoing competition, on the other hand, triggers an incremental process of upgrading and improvement.

A most important game changer in recent transport history is containerisation in combination with globalisation (see also Chapter 4). Containerisation involves a degree of unification, which has boosted handling productivity and facilitated interchange between transport modes. This has led to efficient network connections, reliable delivery and lower costs. It has also fostered a unique expansion of trade, while at the same time spurring globalisation.

Globalisation, in turn, has been instrumental to changes in consumption patterns and production locations, as well as to decreasing costs of commercial transport. The result of this mutual interaction: increasing world trade and cargo volumes. All this has been accelerated and drastically influenced by developments in information and communication technology.

Ports have of course played a key role in these revolutionary developments. They have made sure to facilitate and stimulate containerisation by establishing efficient container terminals and related services. Also, they adapted to the (cost-reducing) trend towards ever larger vessels, by making sure they could accommodate and handle them safely and efficiently. Foresight and pro-active planning are key factors enabling them to make these adaptations on time (i.e. before competitors have taken over their market share).

No doubt, containerisation has been a game changer in commercial transport, but it is not the only one. An unprecedented globalisation has also taken place in other sectors, such a oil, gas, coal and agribulk, often with major discontinuities due to political or social factors. Australia, for instance, is a major source of iron ore, gas and coal, and since China's economy has started growing explosively, Australia's iron ore, gas and coal export to China has grown accordingly. This has evoked such an increase of port activities, that environmental restrictions became a limiting factor.

Changes in infrastructure may also lead to sudden changes in transport networks. A classic example is the opening of the Panama Canal, which suddenly made a number of ports obsolete, especially in South-America. At the same time, the much shorter route provided major competitive opportunities, which triggered the development of the so called Panamax and New Panamax vessel classes, referring to the maximum dimensions that could just fit through the original Panama Canal and the later expansion. This in turn triggered ports worldwide to adapt their infrastructure to accommodate vessels of this size. In Part I – Section 2.1.2 we briefly described the example of the temporary closures of the Suez Canal, in 1956-1957 initiating the construction of larger tankers and dry bulk vessels, and between 1967-1975, which forced the oil sector to develop and use Very Large Crude Carriers (VLCCs) in order to make transport around Africa economically feasible. This accelerated the trend towards larger vessels, which did not reverse after the Suez Canal had been opened again. Every major oil port had to invest in facilities to accommodate these vessels, or otherwise lose its position.

1.2.3 Internal changes

Apart from external changes, there are also internal ones. Every port and terminal goes through a number of stages of life (Figure 1.4), from initiation via growth to maturity and ageing and – if no action is taken – obsolescence. Note that ageing can be technical (infrastructure nearing the end of its lifecycle), but also economic (inadequate response to market changes). Awareness of this lifecycle is crucial for proper port management, if it were only because thinking about and investing in restructuring has to start during the heydays of the port's functioning. This means taking risks at a moment that other people think that everything is going fine.

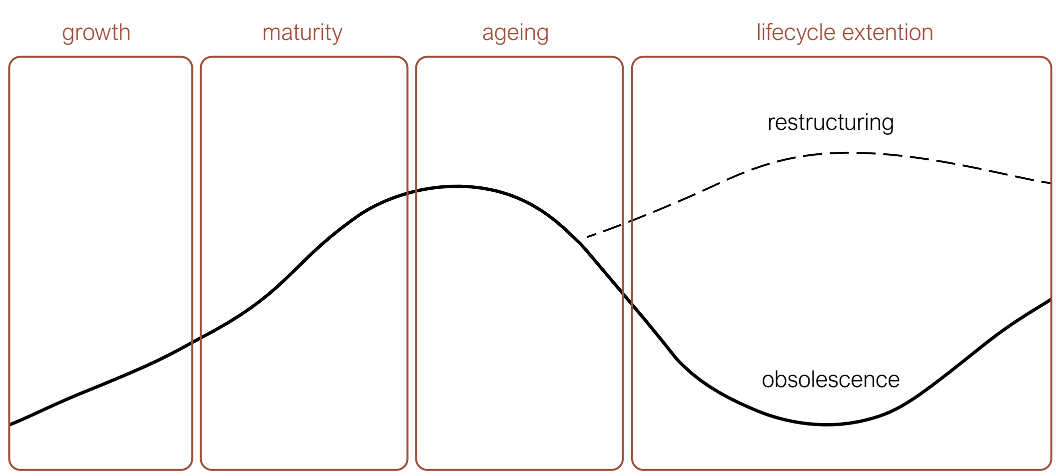


Figure 1.4: Various stages in a port's lifecycle (modified from Charlier, 2013, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

1.3 Port planning

1.3.1 Port development means taking risks

Port infrastructure requires investments that are timely, huge, irreversible, highly risky, and typically have a very long payback period. On the other hand, ports operate in a volatile market and are much more affected by political factors, international trade, and overall world economic conditions than most other enterprises. Ports often have difficulty meeting changes in functional requirements, due to physical limitations and existing infrastructure. Either drastic and costly adaptations are required, or infrastructure has to be decommissioned long before its economic lifetime is over. The overall consequences for the port are, in the best case, inefficiency and loss of competitive position, and in the worst case redundancy and obsolescence. Many older port projects exemplify this. As containerization came with ever larger vessels and required larger areas of land for (un)loading and storage, these ports had to close down or change their function, while new ports in the vicinity took over (Taneja, 2013). One example is the migration to another location of the entire port operation at Helsinki (Figure 1.5, left). The right part of this figure, on the other hand, gives an example of a terminal that completely changed its function.

Figure 1.5: Major port adaptations. Left: the Vuosaari Harbour Project, Helsinki, Finland, where the entire port operation was transferred to a new location in 2008 (Cargo habours to Vuosaari by Pekka Kontiala is licenced under CC BY 4.0); right: Jawaharlal Lal Nehru Port, India, a bulk terminal converted to container terminal in 2006 (View from Cannon Hill on Elephanta Island, Maharashtra, India by A. Savin is licenced under LAL-1.3).

1.3.2 Port master planning and stakeholder involvement

Efficient ports are an important economic, financial and strategic asset to a country. Therefore much attention is paid to port planning in a multi-disciplinary and multi-stakeholder setting. The strategic objectives of government, port authority and other stakeholders, the requirements of port users and operators, environmental issues, the needs of local communities and the embedding in overarching spatial plans are all reflected in a Port Master Plan (Taneja et al., 2008). This includes a layout that allocates land to various uses, reserves space for the future, and outlines the implementation process. Clearly, the Port Master Plan not only serves to prepare the development of the port, but also to win the support of authorities, stakeholders, users and the public at large. This support is instrumental in creating the right conditions for realisation.

A striking example is the extension of the Port of Rotterdam with Maasvlakte 2. Feasibility studies were carried out in the last decade of the 20th century and the government issued a spatial planning decision in 2003. This led to opposition concerning the environmental impacts and in 2005 the Council of State, the highest administrative court in the Netherlands, annulled the decision. Only after an extensive in-depth study of the environmental effects and early involvement of environmental groups, a new planning decision and the Environmental Impact Assessment (EIA) were accepted in 2008. The appeal procedure ended in 2009 with the permission to start the construction. The whole experience was one of the triggers to develop a more nature-inclusive method for infrastructure development, culminating in the Building with Nature (BwN) philosophy (De Vriend and Van Koningsveld, 2012; De Vriend et al., 2015).

1.3.3 Functional designs and order-of-magnitude dimensions

Port planning is more than determining the general layout of a port. Once it is clear which throughputs and which commodities the port is supposed to accommodate, the necessary terminals have to be outlined in a functional design. This means that even this early design stage requires much information, enabling to determine what type of facilities (quays, cranes, storage areas, etc.) are needed and how much space this requires. The results are different for different types of terminals (container, liquid bulk, dry bulk, general cargo, etc.), and also for sea ports and inland ports.

Not every port development is ‘greenfield’, so starting from scratch. More often it concerns the extension or modification of an existing port, or a ‘brownfield’, i.e. an obsolete or derelict industrial area, often environmentally polluted. In the case of a ‘brownfield’ development, the plan must make clear how the required space will be cleared and remediated before becoming available to the new development. The costs involved may be significant and even prohibitive, leading to a different choice of location or a less ambitious plan.

An often arising question is to what extent existing facilities and infrastructure can be used for the envisaged port, under conditions for which they were not designed originally. One example are existing quay walls. They date back a number of years, may on the one hand have been designed with safety margins larger than at present, and on the other hand have degraded through the years. Present-day computer models enable assessment of the actual strength and reliability of these structures, as well as simulating their ageing process (Roubos, 2019). This can save the costs of unnecessary demolition and reconstruction, or the risk of incorporating an unsafe quay wall in the extended port.

It is clear that ports are strategically important and their continuous development is challenging and risky. The best way to cope with this risk is by careful and adaptive planning. The next chapters further elaborate this.

2 Port planning

2.1 The need for port planning

Ports have rarely been planned from the start in their present form. Rather do they continuously develop, meeting ever-changing demands from the supply chain. Yet, there are common factors which historically have determined the location, size and shape of many successful ports:

- *Proximity of a sufficiently deep sea to provide natural access* – through a river mouth or an inlet. Historically important ports such as Guangzhou, Rotterdam, New Orleans or Ho Chi Minh City are located along major rivers, viz. the Pearl River, the Rhine/Maas, the Mississippi and the Saigon River, respectively.
- *Good harbour, providing natural or man-made shelter from waves, wind and strong currents* – New York is an example of a port which is naturally sheltered from the open ocean.
- *Natural access to the hinterland, via rivers or man-made canals, or via major trade routes* – In ancient times, for instance, Mediterranean ports were nodes in the Silk Route.
- *Safe grounds* – quite some city ports are located on naturally elevated land providing protection against flooding and offering a defensive advantage against attackers.
- *Regional and national socio-economic conditions* – such as a nearby urban centre, a large market to serve and the availability of natural resources. Note, however, that these conditions are not a given, as they tend to interact strongly with the presence of the port.

With the growing demand for seaborne trade after World War II and the increasing vessel size and draught, most ports have been expanding/relocating from (historic) city centres inland to locations closer to the coast with better deep-water access (Figure 2.1). Locations on the coast are more exposed to waves, currents and sediments, so they usually require expensive man-made protection structures, such as breakwaters.

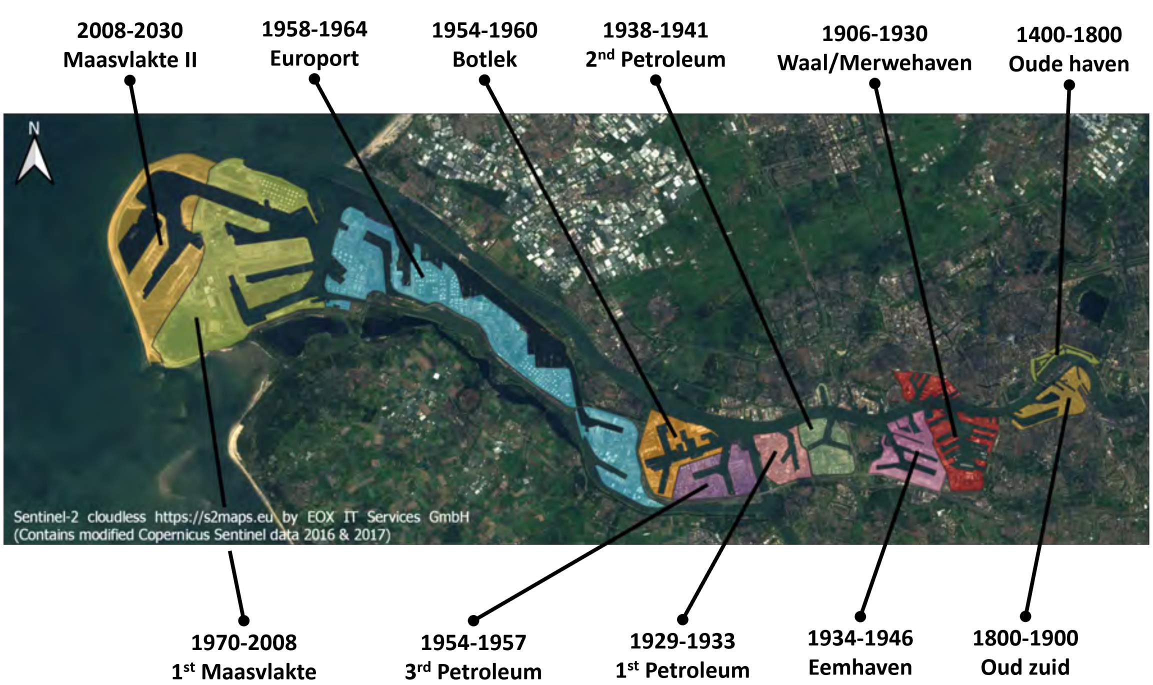


Figure 2.1: Development of the Port of Rotterdam over time (background: Sentinel-2 cloudless by EOX IT Services GmbH is licensed under CC BY 4.0, image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The significance of shipping and ports to the economic development and wealth of cities and countries, from the ancient world up to now, made the construction of ports a matter of great importance. Whereas in natural sheltered areas, ports would develop rather organically, ports built in less sheltered environments for strategic and economic reasons required careful planning. Because of their strategic importance, port planning would mostly be carried out by army engineers, like Vitruvius in ancient Rome. With the development of city and nation states, engineering and port planning became a task of the central government. At present, port planning is mostly carried out by civil engineers employed through Port Authorities which are often central government agencies or consultants.

2.1.1 Port functions

A port is a node in a supply chain, described earlier as the combination of activities and facilities involved in moving a product or good from supplier to customer. This chain generally involves various processing steps at different locations, transport requirements (Figure 2.2) and actors.

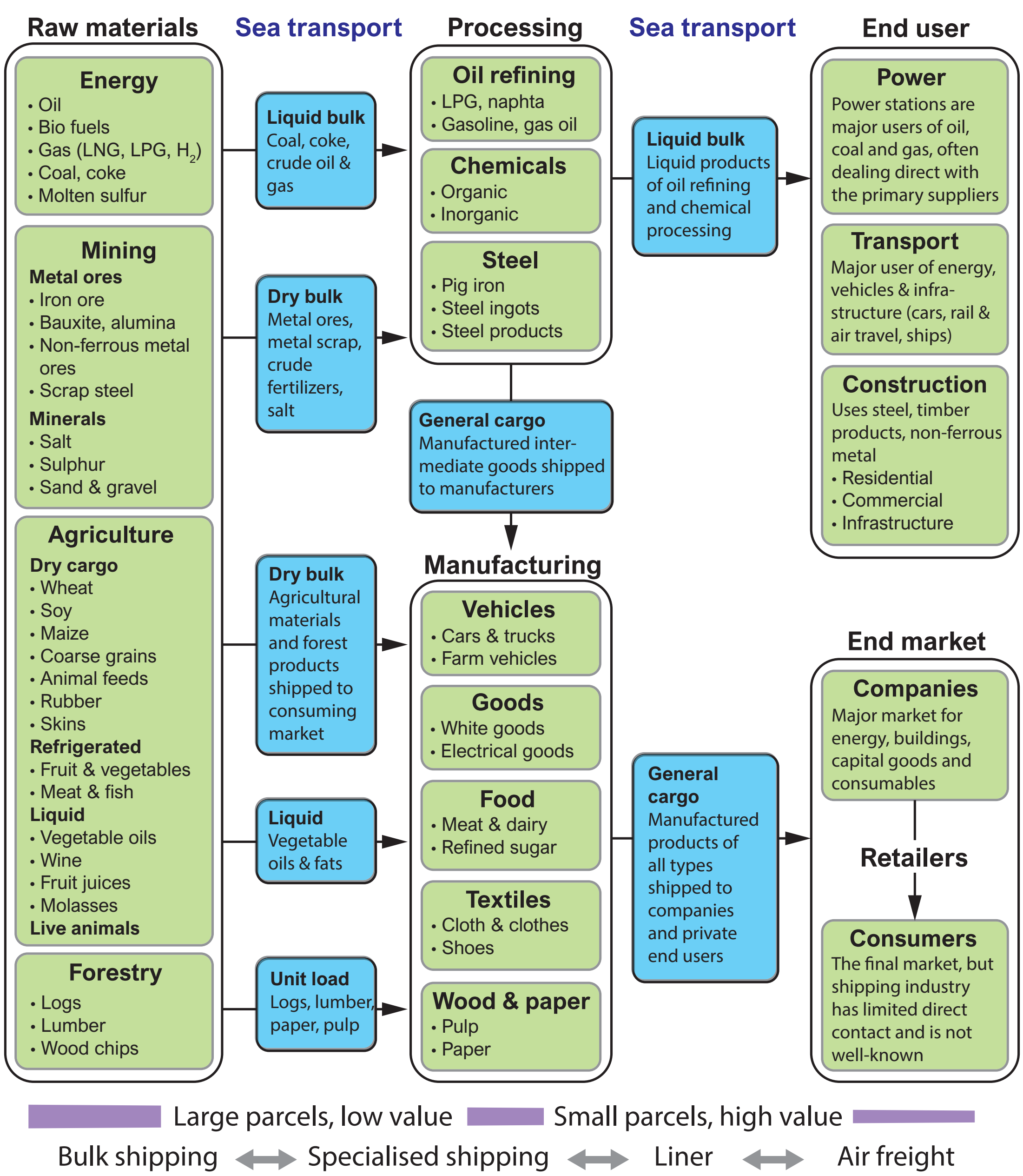


Figure 2.2: Transport requirements in the international transport system (modified from Stopford, 2008, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Understanding which cargo flows can be attracted by the port and what services are required, has a large impact on the planning. To fully understand the cargo flows one should consider the entire supply chain, from source to end costumer (Figure 2.3). The route yielding the most reliable, fastest and least costly delivery will, theoretically, be preferred by shipping companies. However, other market mechanisms, politics and geographical considerations may also play a role.

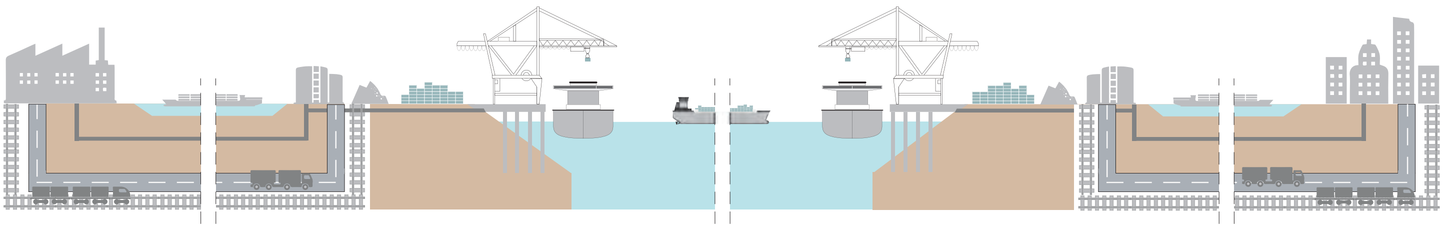


Figure 2.3: Overview of a supply chain, from source to end costumer (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

A commercial sea port has several logistic functions:

1. transfer of cargo from a sea-going vessel to land and vice versa,
2. temporary storage (and sometimes repacking) of cargo,
3. transfer of cargo to inland transport modalities (rail, road, air, IWT, pipeline) and vice versa,
4. (in some cases) processing and/or consolidation of cargo.

Furthermore, sea ports will include a variety of services (pilots, tugs, stevedores, linesmen, bunkering, customs, security, et cetera) and industries adding value to the goods to be imported or exported. To be successful a sea port needs to have good access to sea as well as to the hinterland, and provide sufficient and adequate space and facilities for efficient vessel and cargo operations.

Inland commercial ports have similar logistic functions: mainly transferring cargo from inland vessels to other transport modes and vice versa. They need to have good access to a waterway navigable for vessels of the type and class required to transport the cargo to be handled, as well as proper connections to other transport modalities that can transport the cargo from a production location to the port or from the port to the end customers.

The introduction of the container, in the 1950's, provided a significant boost to international trade. Container transport reduces cargo handling costs, improves security, reduces damage and loss, and allows freight to be transported faster and better on time. Globalisation, a significant decrease of transport costs and ongoing containerisation have yielded a growing market for intermodal transport. On the way to their destination containers usually change several times from one transport mode to another. This underlines the need to consider ports as nodes in a larger logistic chain. Port planning has to reflect this: one cannot develop a viable port without considering its position in this global distribution network.

For further reading see also:

- Stopford (2008) – "Shipping economics, 3rd Edition"
- Ligteringen (2017) – "Ports and Terminals"
- Geerlings et al. (2018) – "Ports and Networks. Strategies, Operations and Perspectives"

2.1.2 Typology of ports

There are many possible categorisations of ports. One may distinguish between sea ports and inland ports, for instance, where, apart from the location, the difference in scale (area, vessel size) is most striking. Yet, the master planning process is largely the same for either type.

One may also categorise ports according to the pre-existing state of the area: 'greenfield' (no existing activities), 'brownfield' (existing port which may require replacement of facilities to meet a growing demand, to fit new transport methods or to upgrade aged infrastructure) or an existing port that is to be extended. This has implications for the master planning, especially if there are nature values involved (compensation measures required), or if the area designated for the expansion is polluted and needs to be remediated.

Ports can also be distinguished by the type of cargo (containers, dry bulk, liquid bulk, etc.). Since most larger ports typically deal with multiple types of cargo, however, categorisation by cargo type is more suitable for terminals (see Chapter 4 and Chapter 5). A useful distinction from a port planning and management perspective is the following:

- *single-use ports* – such as fishery ports, container ports, oil ports, ferry ports, passenger ports, et cetera;
- *multi-use ports* – handling a variety of cargo types; and
- *industrial ports* – usually serving a single factory or plant, such as a refinery, a power plant, a steel mill, a beer brewery, et cetera.

Ports can also be distinguished by their management model. Port management models depend on the port's function, size, history, regional context, national public political structure and private involvement. The World Bank Port Reform Toolkit (World Bank, 2007) describes four of these models in detail. Figure 2.4 illustrates how each type is characterised by a distinct combination of public and private responsibility. We will briefly summarise them here, using the same terminology.

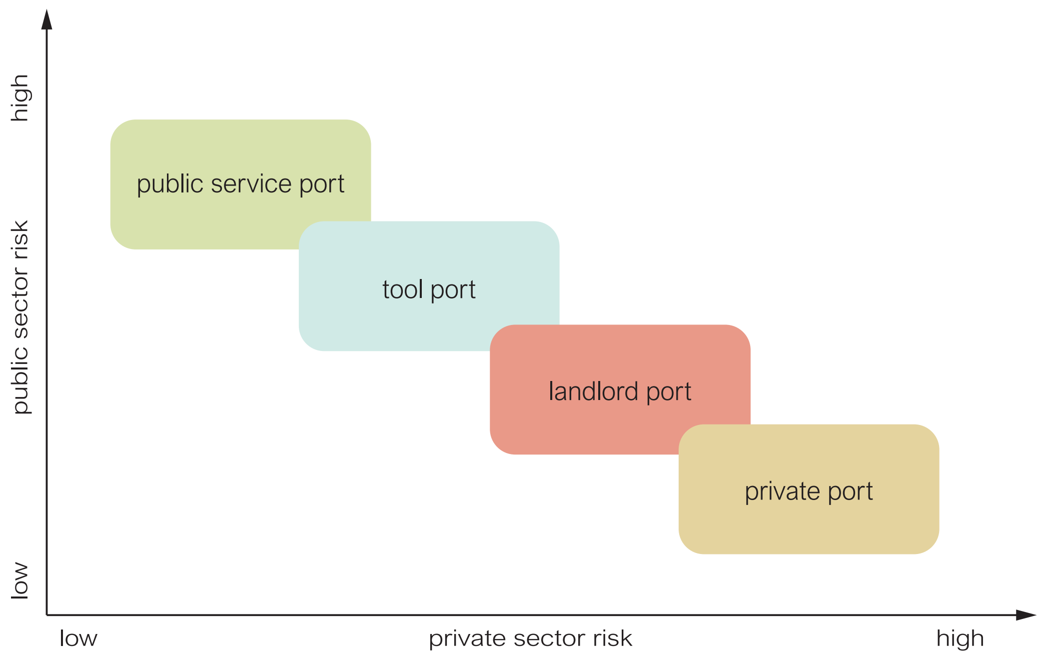


Figure 2.4: Port models distinguished by alternative combinations of risk-sharing between public and private sectors (reworked from Herrera Dappe and Suárez-Alemán, 2016, which is licenced under CC BY 3.0 IGO, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

A **public service port** has a management structure with the port authority or another public agency offering the complete range of services required for the functioning of the port system. The authority owns, maintains, and operates every available asset, and cargo handling staff is employed directly by it. This management model is on the decline and found only in some developing countries. The main disadvantage is the lack of competition, which leads to inefficiency, insufficient innovation and bureaucracy.

In the **tool port** model, the port authority owns, develops, and maintains the port infrastructure as well as the superstructure, including cargo handling equipment such as quay cranes and forklift trucks. Port authority staff usually operates all equipment owned by the authority. Other cargo handling, e.g. on berthed vessels and on land terminals, is usually carried out by private cargo handling firms contracted by the shipping agents or other principals licensed by the port authority. This type of port model shares the above-mentioned disadvantages of the public service port model. The model is, however, found attractive for ports that are in transition to a landlord port model. By limiting the initial investments for the private sector, confidence in the private sector can be developed and investment risks are reduced.

In the **landlord port** model the port authority or another relevant public agency owns the port land and is responsible for port planning and development, as well as for the maintenance of basic port infrastructure and aids to navigation. This is currently the dominant port model, with examples such as Rotterdam, Singapore and

New York. The main advantage of this port model is that private companies are generally better capable to cope with market requirements. Also, cargo handling operations are more efficiently organised by a single private company. At the same time, large capital investments (such as breakwaters and reclamations) remain with the central government, hence reducing investment risks for single operators. The latter is also a weakness of the landlord port model; significant port extension needs to be carefully planned to accommodate market conditions and misjudging the timing of extension may lead to inefficient use of (significant) public funds.

In the **build, operate and transfer** model private sector parties are responsible for most of the civil engineering infrastructure and all of the equipment. The port authority is only responsible for ensuring that the private operator has the rights to build and operate the terminal. This model is a fall-back option for port authorities that have insufficient means to acquire the infrastructure needed in a landlord port model.

In fully **privatised ports** public entities no longer have any meaningful involvement in the port. Pilotage is often the only service provided by the government, as the safety of waters and other users may be concerned. The port land is privately owned, unlike the situation in other port management models. Ports in the UK are a good example, or ports which are part of large industrial complexes such as refineries. The main advantage of this model is that maximum flexibility is provided to investment and port operations by private companies. The major disadvantage is that monopolistic behaviour may limit the further addition of value to society.

The port management model determines who will be responsible for the design, development, operation and maintenance of the various elements of the port. In the landlord port model, for instance, the port authority will prepare a cargo forecast and develop a port layout that accommodates a number of terminals suitable for the expected commodities and cargo flows. The individual terminals, though, will be designed, built and operated by private companies. In such a model, it is very important that private companies are involved in an early stage of project development, to ascertain that the port infrastructure meets the demand. Furthermore, flexibility, expandability and adaptability are important to accommodate changes in the (future) needs of private terminals operators.

For further reading see also:

- World Bank (2007) – “Port Reform Toolkit (2^{nd} Edition)”
- Geerlings et al. (2018) – “Ports and Networks. Strategies, Operations and Perspectives”

2.2 Port planning process

2.2.1 Masterplan objectives

A port masterplan establishes policies and guidelines to direct the future development of a port. The principal objectives of developing a port masterplan are to (see PIANC, 2014d):

- develop and communicate a vision for the port to the wide range of stakeholders,
- integrate economic, engineering, environmental and safety considerations in the overall plan,
- promote the orderly long-term development and growth of the port by designating functional areas for port facilities and operations,
- enable the port to flexibly respond to technological innovations, cargo trends, regulation and legislation changes and port competition, and to
- develop the port in accordance with international and national legislation and guidelines, including its embedding in the existing spatial planning context.

The viability of a port development depends on the physical, environmental and socio-economic characteristics of the location. By providing space and favourable conditions for supporting services and other port-related activities, the number of stakeholders and potential financiers can be increased. Considering the often large investments required from public and private budgets, financing and economic feasibility are guiding principles throughout the port masterplan development. Master planning therefore involves a wide variety of expertise (Figure 2.5).

Figure 2.5: Expertise involved in port planning (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

2.2.2 Planning process

To develop a port masterplan, the following aspects need to be addressed:

- *Port strategy* – defines the objectives and strategy of the port development. What does one want to achieve with this port? What type of cargo flows shall it handle? Who will be the customers? What hinterland shall it serve? What industries shall it accommodate? Et cetera.
- *Cargo and vessel forecast* – identifies throughput per type of cargo to be expected and the numbers and sizes of vessels to be handled for this.
- *Physical site conditions* – topography, subsoil, exposure to extreme weather conditions, et cetera.
- *Nautical access and port water areas* – Is deep water access available, or is dredging required? What is needed in terms of in-port traffic channels, turning basins, harbour basins, et cetera.?
- *Hinterland connections* – for different transport modes (rail, road, IWT, air, pipelines).
- *Environmental and social aspects* – environmental impacts to be expected, labour market, hindrance, et cetera.
- *Stakeholders* – identification, interests, interrelationships.
- *Safety* – individual risks, public health risks, hazardous cargo, et cetera.
- *Financial and economic feasibility* – costs vs. benefits, capital risks, financing structure, potential financiers.

Before concrete planning, design and construction of a port come within sight, a range of studies and design activities have to be performed and many crucial decisions taken. For example: a first orientation on supply and demand, port type selection, possible role in the transport network, site selection, embedding in existing spatial plans, choice of a port management model, designing port infrastructure and costing, et cetera. Typical steps in the development of a port, or elements within an existing port, involve the following:

- *Pre-feasibility studies* – aiming to explore an initial idea and to develop a port strategy. During this stage, the focus is often on economic studies and policies to identify clearly the "need" for a port. Little to no site surveys are carried out and engineering design development is often limited. The most prominent (economic, financial, environmental, political etc.) risks will be identified. Results are laid down in a Strategic Master Plan that presents the functional requirements of the port.
- *Feasibility studies* – including Basic Design (BD) or Front End Engineering Design (FEED) studies. This project step should conclude whether a project is feasible and steps towards implementation can be started. The functional requirements of the Strategic Master Plan are translated into a port layout and concept design of significant structures (e.g. breakwaters, reclamation, quay walls, dredging). Engineering design development during this stage should be sufficiently detailed for an accurate cost estimate, which will be

used in detailed financial and economic evaluations. Site surveys will be carried out to serve designs and to limit any unforeseen construction risks during project implementation. Other opportunities and risks which may affect the feasibility of the project will be further identified, through social and environmental studies and through stakeholder engagement. Figure 2.6 outlines this process.

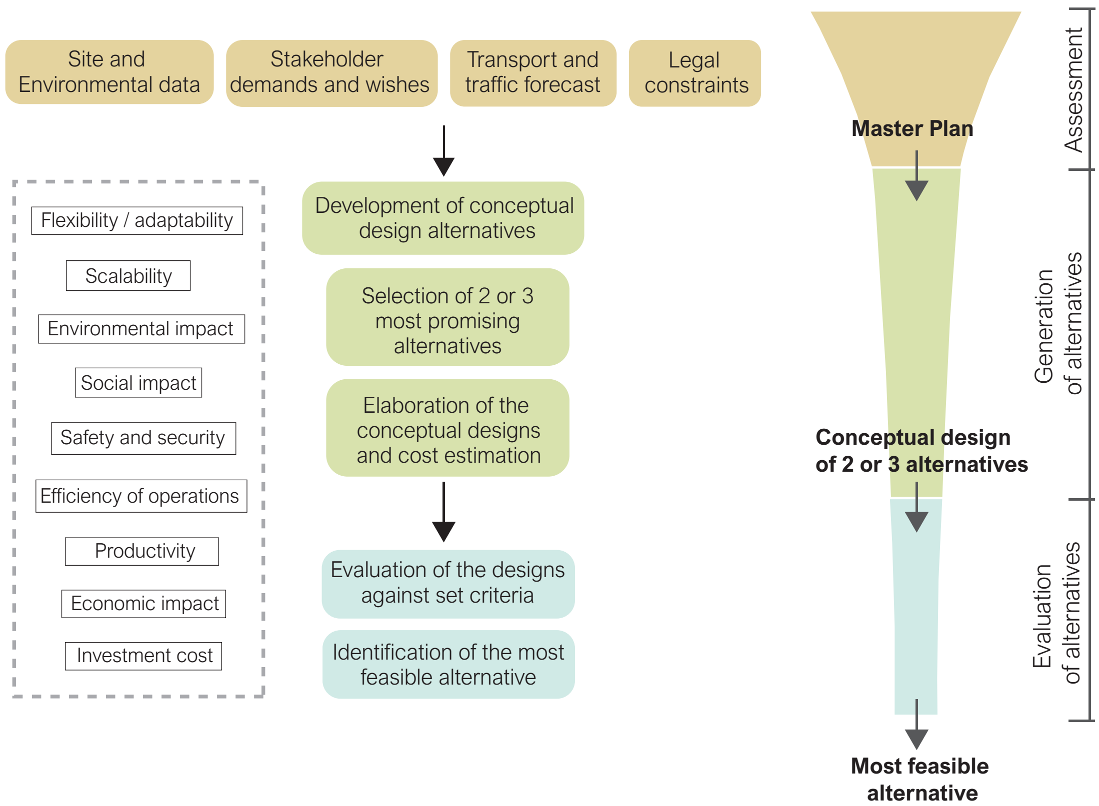


Figure 2.6: Flow chart of a port feasibility study (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

- When the project is deemed feasible, the EIA process can be completed in order to acquire planning permission and the necessary permits. Once the necessary permits and financing has been arranged, realisation of the port, either in whole or in parts, can start. There are in general two options:
  1. A marine contractor is procured through a tender process whereby the contractor – depending on the contract form chosen (see Part I – Section 2.2.4) – bids for further designing and/or building the (port) structures. A type of contracting combining the two is usually referred to as Design and Build (D&B) or Engineering, Procurement, Construction (EPC) contracting. The contractor will carry out further surveys and prepare detailed designs for construction. The EPC contractor will, after approval of the detailed designs, build the port structures. This type of contract has become more popular due to better utilization of the contractor's expertise and more competitive bidding. Disadvantage of this type of contracting is that the contractor is increasingly liable for the successful completion of the project. In many cases this has led to significant cost overruns, disputes and delays, especially if project owners are making additional demands, or if the project has not been well defined during the FEED stage.
  2. The FEEDs are worked out into a detailed design by the project owner (in this case a Port Authority, that usually hires an engineering consultant). The detailed design will be tendered to a marine contractor using a Construct Only (CO) contract. This type of contracting is more traditional and typically suitable for smaller works or Project Owners who have sufficient capability for inhouse or outsourced engineering.
- Once construction is completed, the port site or terminal areas are handed over to the Port Authority. In case of a landlord port model, only the terminal terrains have been built by the Port Authority and the terminals themselves, including superstructures such as cranes, buildings et cetera, will be developed by terminal operators.

Figure 2.6 gives a schematic overview of the Feasibility study phase. The feedback arrows signify that the outcome of each sub phase may be re-evaluated based on additional information that came to light in a later sub phase. This even goes for the conclusions of the pre-feasibility study. Should the feasibility study show that the port is not economically feasible, for instance, revision of the cargo forecasts and the subsequent conceptual designs will be necessary. Developing and comparing multiple design alternatives throughout the port development process is therefore beneficial, as this gives additional insight and options for mitigation in case obstacles are encountered along the way. When properly managed, this iterative design process can converge to a better solution than initially found (see Figure 2.7).

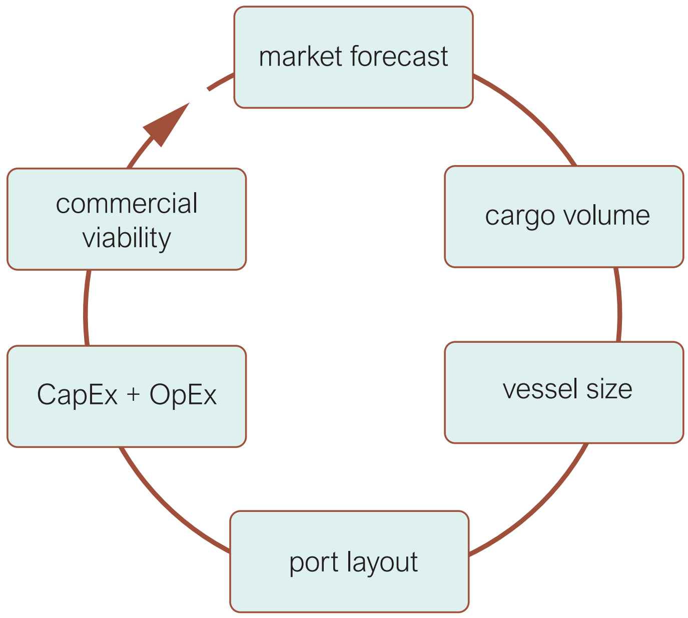


Figure 2.7: Iterative process in port development (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

In the following sections we will go through the key steps of this process, which ultimately leads to the Port Masterplan.

For further reading see also:

- Thoresen (2018) – “Port Designer’s Handbook. Fourth edition”
- PIANC (2014d) – PIANC Report N°158 “Masterplans for the development of existing ports”
- Ligteringen (2017) – “Ports and Terminals”
- PIANC (2019c) – PIANC Report N°185 “Ports on greenfield sites - Guidelines for site selection and master planning”

2.3 Cargo and vessels

2.3.1 Cargo forecast

A cargo forecast is one of the first steps in the development of a port masterplan (Figure 2.6) and typically encompasses:

- cargo type,
- cargo volume,
- growth projections, and
- future scenarios.

The cargo forecast is the basic information for establishing the required capacity of the port. The financial and economic success of a port depends on how much cargo can be handled and what competitive fee can be charged for the port services provided. Attracting cargo to a port, however, depends on many uncertain factors and is therefore difficult to predict. Moreover, ports are often in fierce competition, so the plans of neighbouring ports need to be considered. There are in principle three methods for a cargo forecast:

1. *Top-down* – start from the macro-economic development of the region (e.g. population, Gross Domestic Product (GDP), trade volumes) and link these developments to estimated cargo flows to and from the hinterland.
2. *Bottom-up* – start from the micro/meso-economic development of industrial companies/sectors that use (or are intending to use) the port and aggregate the cargo flows involved.
3. *Logistical modelling* – use a global logistics model to estimate the port's throughput volumes when adding it as a new (or modified) node to the transport network.

From a cargo forecast perspective, one further distinguishes two types of cargo:

- *captive cargo* – destined to industries in the vicinity of the port, without any alternative port option. The cargo forecast is based on a bottom-up approach. Typical captive cargo would be Liquified Natural Gas (LNG) imported for gas-fired power plants located near the port or iron ore which is exported through the port from a nearby mine.
- *contested cargo* – of which the users are located in the hinterland and have the choice between various competing ports. This type of cargo is also called "footloose". Which port is chosen depends in the end on costs, reliability and on-time delivery. Containers are often contested cargo for which ports compete. The ports of Antwerp, Rotterdam and Hamburg, for instance, compete for a market share for the Northwest European hinterland. The volume of contested cargo is usually determined through a mix of top-down and logistical modelling methods.

Top-down approach The basic information needed for a top-down cargo forecast concerns regional economic parameters such as population, GDP, industrial activities, trade volumes, et cetera, now and in the future. They are linked to cargo flows from and to the hinterland. To estimate container throughput, for instance, one may calculate how many consumer goods are typically expected to be imported into a region or country. Typical values are 0.5 Twenty Feet Equivalent Units (TEU) per person per year for highly developed countries, down to 0.05 or less TEU per person per year for developing countries. This approach usually starts from historic trends and extrapolates these into the future, following the expected population and GDP growth. This type of forecasting is especially relevant for commodities related to general consumption, such as Fast Moving Consumer Goods (FMCG).

Bottom-up approach A bottom-up cargo forecast starts from the development plans and expectations of individual sectors that use ports for import and export. Volumes are aggregated and yield a transport demand per type of cargo. This approach is relevant for commodities such as bulk cargo for industries (steel mills, wood processing, etc.), for the energy sector (gas, coal, etc.) and for raw materials, components and products of specific industries (cars, steel etc.) in the vicinity of the port.

Logistical modelling Cargo forecasts based on logistical modelling use an economic transport model (time, costs and reliability) to estimate the cargo flows in a network of transport links and ports. It is relevant to the development of a port to know the extent to which its future presence/state has the potential to shift traffic flows of contested or footloose cargo from one transport corridor to another. The general assumption is that shipping agents will ultimately choose the most beneficial transport route from origin to destination in terms of costs, time and reliability.

Figure 2.8 shows an example from West Africa. Here a number of ports compete for cargo to and from the fertile plains of the hinterland. The transport costs of each corridor can be compared (Figure 2.9), based on which the most promising location for a port development can be selected. It may be clear that a "full logistic chain" approach is very important and that port development cannot be considered independently of the developments in the hinterland. Often, corridors have "dry ports", where cargo transfer or consolidation is organised in a similar way as in sea ports. Dry ports are developed close to economic centres or at nodes between multiple corridors.

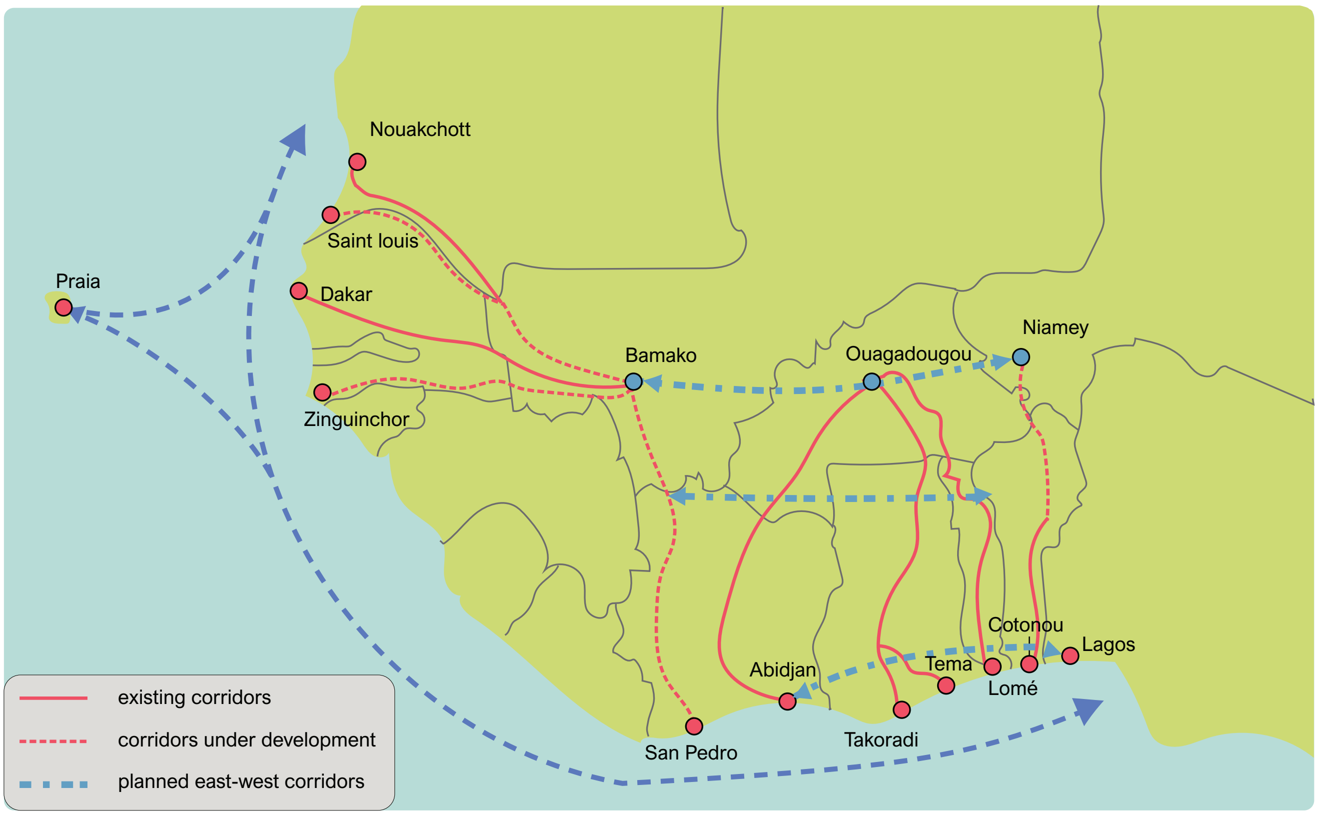


Figure 2.8: West African ports and corridors (source: Royal Haskoning DHV, image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

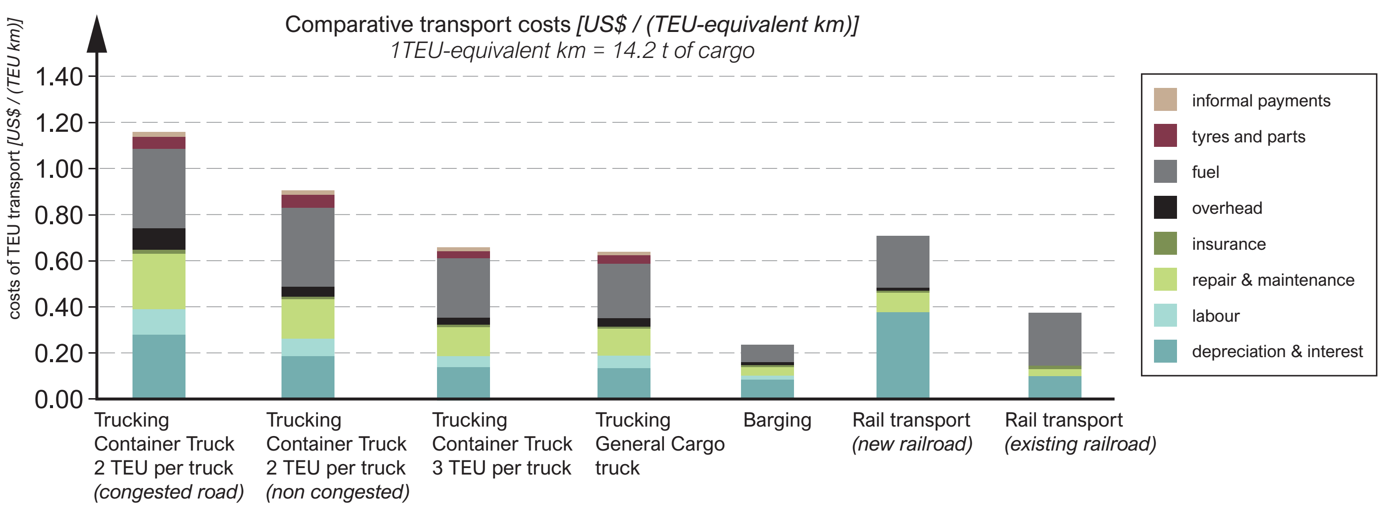


Figure 2.9: Transport costs for the various corridors estimated by logistical modelling (source: Royal Haskoning DHV, image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The output of a cargo forecast (Figure 2.10) is the basis of a port masterplan. The future is uncertain, however. Hence there will always be a large uncertainty around any cargo forecast. This explains why economists commonly work with scenarios that reflect potential future developments, such as “low”, “medium” and “high” scenarios for GDP growth, hinterland development, interest of private companies, competition, etc. These scenarios show what steps actors and stakeholders need to take to make the port development a success. Port planning should take into consideration these uncertainties, such that future development can be accommodated within the port. Given all these uncertainties, it is important to involve major stakeholders, such as large shipping lines, container terminal operators, bulk storage companies and local industries, in an early stage of development of the new or upgraded port.

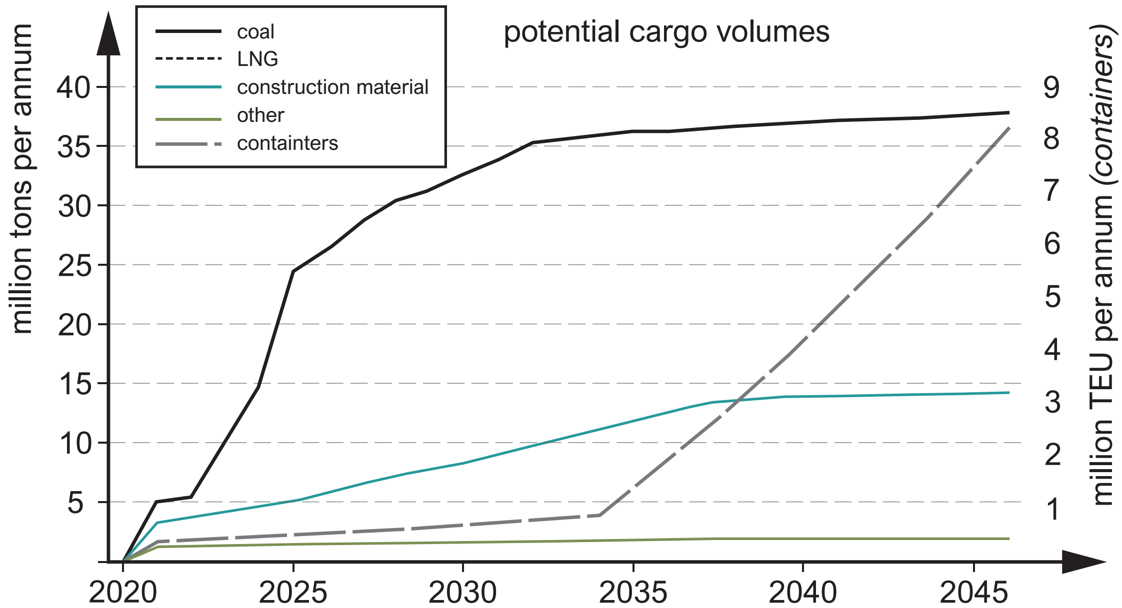


Figure 2.10: Example of a cargo forecast (source: Royal Haskoning DHV, image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

2.3.2 Vessels

Next to the type and amount of cargo that is expected to flow through the port, the number and size of the vessels that are anticipated to be involved are important for port planning.

Vessel classification

Vessel types and sizes differ according to the type of cargo that is carried, or according to the function. The widely used IHS Maritime (IHSmarkit.com) register of ships considers the following vessel classes:

- Cargo carrying vessels
  - Tankers
    - Oil
    - Liquified gas (Liquified Petroleum Gas (LPG), LNG, etc.)
    - Chemical
  - (Dry) Bulk carrier
  - Dry Cargo/passengers
    - General cargo
    - Containers
    - Ro-Ro
    - Passenger liner, cruise and ferries
    - Refrigerated cargo ship (Reefer)
    - Other dry cargo (e.g. livestock)
- Working vessels
  - Fishing
  - Offshore
  - Towing/pushing
  - Dredging
  - Other activities (e.g. pilot vessel, ice breaker etc.)

Other registers, such as Lloyd's, Clarkson's or Q88, use different classifications.

Vessel size and load capacity

The most often used parameters to defining a ship's size and/or load capacity are (Puertos del Estado, 2007; PIANC, 2014d):

- *Dead Weight Tonnage (DWT)* – maximum load plus fuel, lubricating oil, water, stores, crew and supplies in tons (t). This parameter is often used to define 'weight' carriers.
- *Gross Tonnage (GT)* – although expressed as a 'tonnage', it is a nondimensional quantity. It is actually a complex measure of the overall internal volume of the ship's enclosed spaces according to the International Maritime Organization (IMO)'s 1969 International Convention on Tonnage Measurement of Ships. The GT is often used to define 'volume' carriers. GT has officially replaced the earlier measure Gross Registered Tonnage (GRT), which is a vessel's internal volume or capacity measured in Moorsom tons or registered tons. The Moorsom ton is equivalent to 100 cubic feet, 2.83 m^3.

For a number of vessel types, cargo specific parameters have been defined to indicate load capacity. For instance:

- *Twenty Feet Equivalent Units (TEU)* – as a measure for the capacity of container vessels,
- *Cargo volume (m^3)* – for LNG, Compressed Natural Gas (CNG) and LPG carriers,
- *Car Equivalent Unit (CEU)* – for car carriers,
- *Lane-metres (m)* – for Ro-Ro vessels, and
- *Number of Passengers (PAX)* – for passenger vessels.

It should be noted that load capacity does not have direct implications for the specific dimensions of the vessels a port has to accommodate, or about the design vessel for which the port will have to be designed. For this a port developer typically thinks in terms of vessel classes.

Vessel classes

Early in the port development process, the project proponent needs to decide for which vessel class(es) the port infrastructure shall be designed. A vessel class represents a range of vessels of largely the same dimensions. Variations in dimensions within each class are a result of varying ship building practices at shipyards, varying user requirements and developments over time.

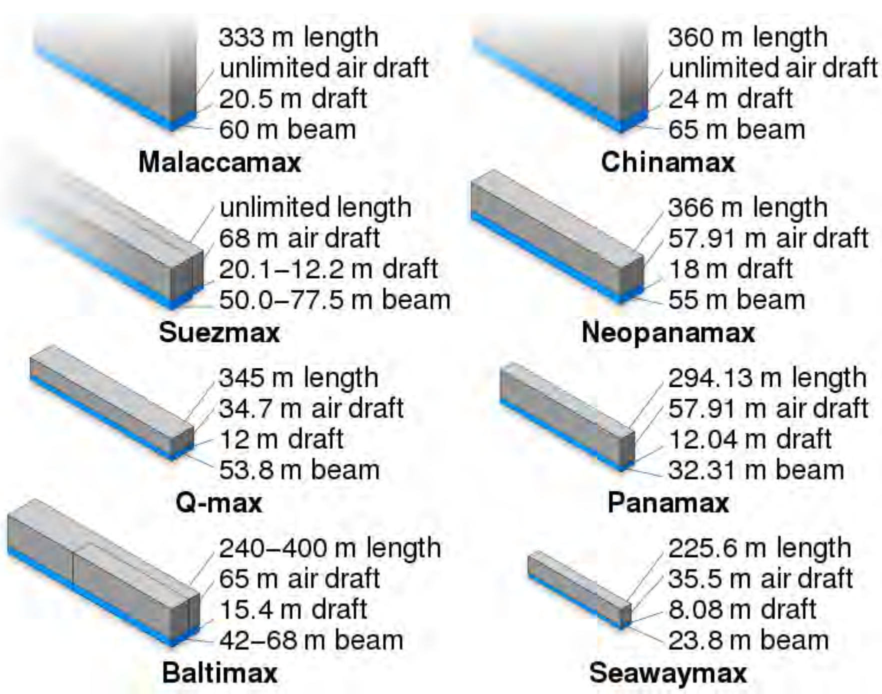


Figure 2.11: Ship measurements comparison of various vessel classes (by Cmglee is licenced under CC BY-SA 3.0).

Vessels classes have been introduced over time, often in connection with physical restrictions along main transport routes (Figure 2.11). The Panamax class, for instance, concerns a vessel with optimised dimensions for the (old) Panama Canal, whereas the Suezmax refers to the class of vessels that just fits the Suez Canal. There is a range of other similar classes for sea going vessels: i.e. Seawaymax, Handy size, Handymax, Capesize, Chinamax, Aframax, Q-M, VLCC, Ultra Large Crude Carrier (ULCC), each with its own backgrounds.

Some of these vessel class names have become a bit confusing over the years. Since the Panama Canal has been expanded, for example, the New Panamax class refers to the class of vessels that just fits the expanded Panama Canal. Yet, the vessel types referred to as Panamax still comply with the old dimensions.

Vessel dimensions

Figure 2.12 illustrates the definition of a number of vessel dimensions that are important for ports and waterways design. It shows the:

- *beam, B_s* – the width amidships at the waterline;
- *length overall, L_{OA}* – the maximum length of a vessel's hull measured parallel to the waterline;
- *length at the waterline, L_{WL}* – the waterline length if the vessel is at rest. The L_{WL} may vary depending on load, and is typically shorter than L_{OA};
- *draught, D_s* – the vertical distance between the water line and the keel;
- *air draught, D_{air}* – the vertical distance between the water line and the highest point of the vessel;
- *water displacement, Δ* – which, according to Archimedes' principle, equals the vessel's weight; and
- *block coefficient, C_B* – the ratio of the vessel's underwater volume to the volume of a rectangular block having the same overall length, breadth and depth.

The length between perpendiculars (L_{BP}) is of less importance to port and waterway design, but rather serves as an indication of the load capacity.

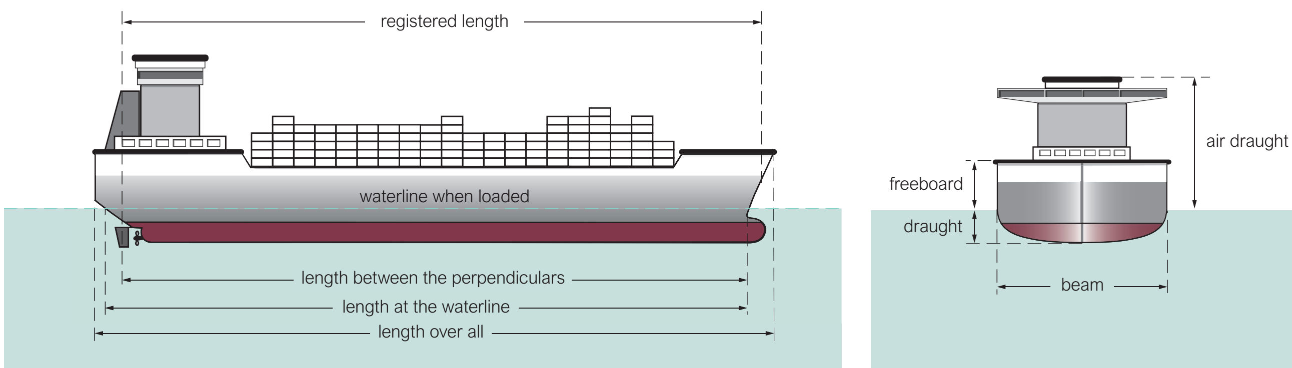


Figure 2.12: Vessel dimensions (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Design vessel concept

Port structures and water areas, as well as navigation channels and waterway structures, are usually designed for a 'reference vessel' or 'design vessel'. Obviously, a variety of vessels will use them, but the design vessel determines their dimensions and other relevant properties, such as strength. Using a single set of inputs facilitates the design process. The definition of the design vessel can vary between applications (see, for instance, ROM 3.1-99 Part III Puertos del Estado, 2007):

- The vessel dimensions and related carrying capacity exceeded by 50% of the vessels in a certain class may be used to determine the terminal throughput or average storage requirement.
- The dimensions exceeded by only 10% of the vessels can be used to determine the berth length or the access channel length and width.
- Vessel dimensions extrapolated to 110% of the maximum are used to design jetties and mooring structures.
- Et cetera

This statistical approach requires a statistical analysis of the fleet that can be expected to call at the port to be designed. Figure 2.13 gives an example for the global fleet in different DWT-classes, with draught as a statistical parameter.

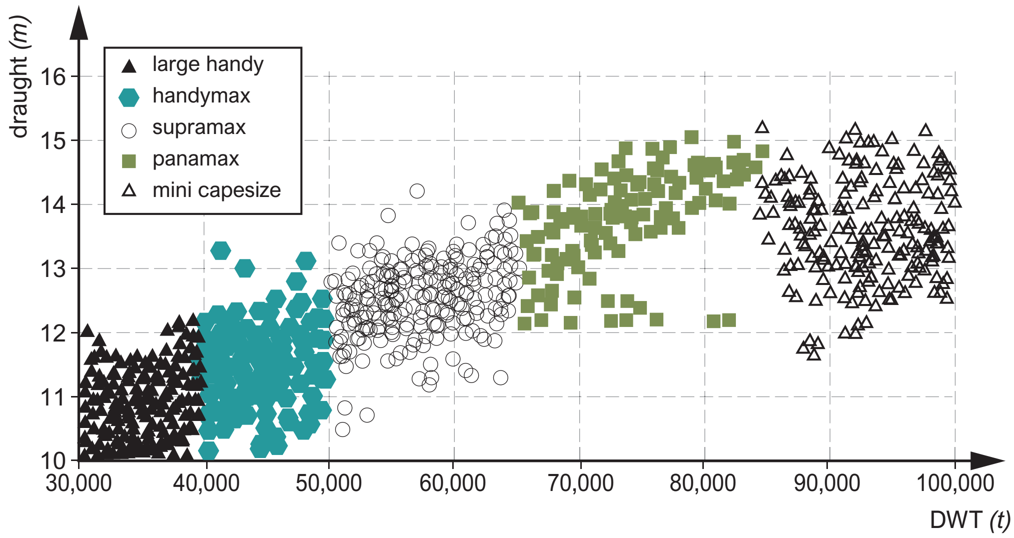


Figure 2.13: Scatter diagram of vessels draughts in various DWT-classes (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Container vessels, however, are seldom fully loaded or completely empty, not only because they may be loaded with both loaded and empty containers, but also because they often operate in roundtrips (De Jong, 2020). In addition, single containers often contain lightweight consumer goods and are therefore not loaded up to the maximum load (payload) of a container.

Vessel trends

Vessel sizes and fleet mix vary over time and the ship building industry shows various cycles of increasing vessel sizes and consolidation. Driving factors for changing vessel sizes are:

- Economies of scale of larger vessels
- Parcel size
- Physical restrictions
- Shipping costs

For further reading see also:

- Stopford (2008) – “Shipping economics, 3rd Edition”

2.4 Physical site characteristics

The physical site characteristics are key information to port planning and design. Site data collection is particularly relevant for greenfield ports, where site data are generally scarce. Open source data can assist in early stages of the project, but site surveys including in situ measurements are required for further detailed design activities.

2.4.1 Site selection

Finding a suitable site can be of paramount importance for the feasibility of a greenfield port. Site selection involves the evaluation of various alternatives. Initial site screening will focus on qualitative aspects, whereas the final site selection will involve a detailed comparison of a reduced number of alternatives. Important aspects often concern costs, risks and opportunity benefits, such as:

- Construction aspects (dredgeability, constructability, maintenance dredging requirement),
- Environmental and Social Impact Analysis (ESIA) aspects (environmental sensitivity, social sensitivity, political sensitivity, morphological impacts),
- Port planning aspects (nautical accessibility, land suitability, hinterland access, phasing flexibility),
- Existing port infrastructure (marine infrastructure, land-based infrastructure, hinterland access).

An example of a qualitative evaluation is presented in Figure 2.14. In the next subsections we highlight a number of physical site characteristics that port developers should consider carefully.

	Assessment Criteria	Based upon information	Sub criteria	Liberia								Yvory Coast			
				Zone 3		Zone 4						Zone 5		Zone 6	
				A	B	C	D	E	F	G	H	I	J	K	L
Construction aspects	Dredgeability	geology, coastal profile, sediment characteristics	quality of soil	3	3	3	3	3	3	3	3	3	3	3	3
			distance to 25m depth contour	2	2	2	2	2	2	1	1	1	1	1	1
	Constructability	geology, coastal profile, waves, presence of construction port	wave height	3	3	3	3	3	3	3	3	3	3	3	3
			soil conditions onshore	1	1	1	1	1	1	1	2	1	3	1	1
			soil conditions offshore	2	3	2	3	2	2	2	1	2	2	2	2
			construction port	1	1	1	1	1	1	1	1	1	1	1	1
	Maintenance dredging	coastal profile, sediment characteristics	distance to 25m	3	2	2	1	2	2	1	1	1	1	1	1
			sediment transport	2	2	1	1	1	1	1	1	1	1	2	2
ESIA aspects	Environmental sensitivity	flora and fauna, turbidity	onshore restrictions	2	2	2	2	1	2	2	1	1	2	3	2
			marine restrictions	2	2	2	2	2	2	2	2	2	2	3	2
	Social sensitivity	presence of settlements, fishing grounds	population	3	3	1	2	1	1	1	2	2	3	2	3
			sea use	2	2	1	1	2	1	1	1	2	2	2	1
	Political sensitivity	crossing of borders	border	2	2	2	2	2	2	2	1	2	2	2	2
	Morphological impacts	sediment, coastal characteristics	erosion	2	2	1	1	1	1	1	1	1	1	2	2
			property value	1	3	1	2	1	1	1	2	2	2	2	2
Port planning aspects	Nautical accessibility	waves, tides, wind conditions and available space	waves	3	3	3	3	3	3	3	3	3	3	3	3
			tide	2	2	1	1	1	1	1	1	1	1	1	1
			current	1	1	1	1	1	1	1	1	1	1	1	2
			marine obstructions	1	1	1	1	1	1	1	1	1	1	1	2
	Land suitability	topography, land use	elevation	3	1	2	1	2	2	3	1	1	3	3	1
	Hinterland access	existing rail and road connections	road	1	1	1	1	1	2	2	2	1	1	1	3
			rail	2	2	1	1	1	2	3	3	3	3	3	3
	Phasing flexibility	available land	area availability	2	3	1	2	1	1	1	3	1	2	3	3
Existing Port Infrastructure	Wet infrastructure	channel, basin and breakwater	channel & basin		2		3			3	3		3		2
			breakwaters		1		1			3	3		3		1
			expandability		2		2			1	2		2		3
	Land infrastructure	storage yard	available / expandable		3		2			1	3		2		2
	Hinterland access	existing and road connections	road		2		1			2	2		3		2
			rail		2		1			3	3		3		3
			Expandability		1		1			1	3		3		3
Ranking															
		critical criteria	not passing	1	3	1	1	1	1	1	3	1	1	3	3
		score	scale 1 - 10	5.0	4.8	7.2	6.7	7.2	6.7	6.7	6.7	7.0	5.4	5.0	5.0
		ranking	#	9		2	4	1	5	6		3	7		

Figure 2.14: Structure of a qualitative evaluation chart of port sites (by Royal Haskoning DHV is licenced under CC BY-NC-SA 4.0).

For further reading see also:

- PIANC (2019c) – PIANC Report N°185 "Ports on greenfield sites - Guidelines for site selection and master planning"

2.4.2 Topography and bathymetry

A port generally requires a significant area of reasonably flat land. The existing topography needs to be known in order to estimate the amount of earthmoving needed to prepare the site. Sometimes part of the area has to be reclaimed, which means that also the nearshore bathymetry needs to be known. The costs involved in these types of site preparation can be substantial.

The water depth determines the draught of the vessels that can access the port. Dredging or breakwater construction are significant cost items and greatly depend on existing water depths. UK Admiralty Charts (Figure 2.15) are available for every navigable sea around the world. However, these charts focus on navigability and therefore do not always give the exact bathymetry, rather they indicate the minimum depth.

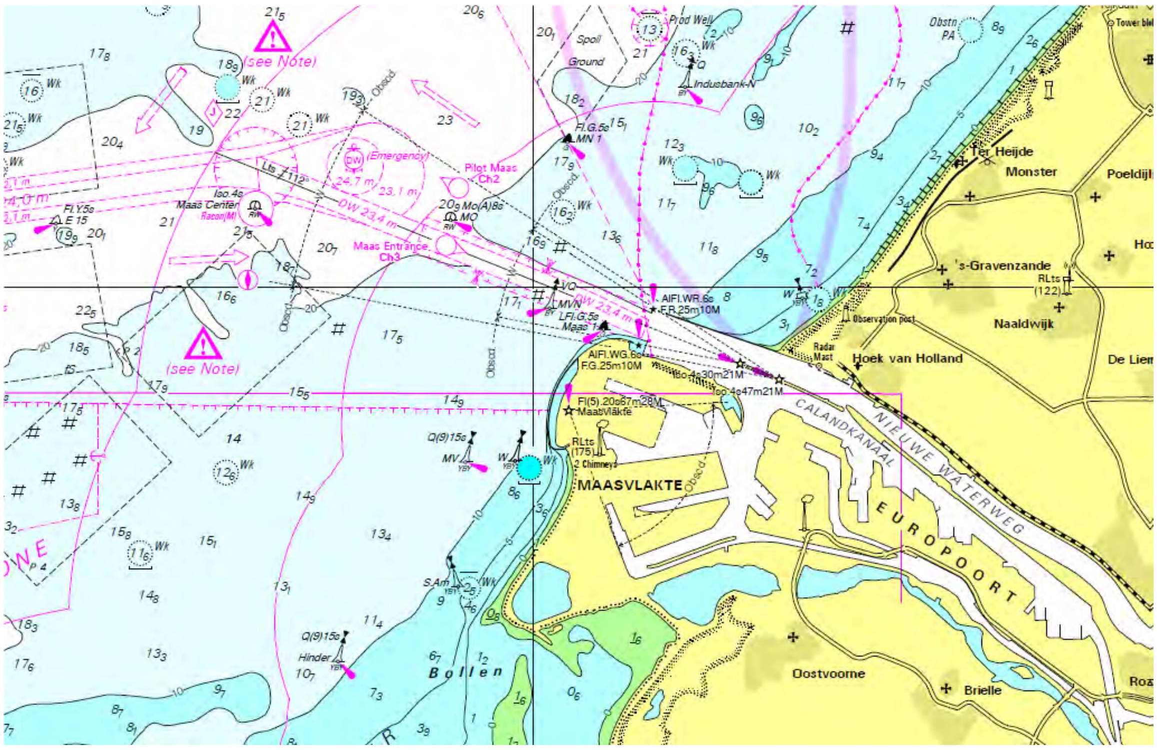


Figure 2.15: Bathymetric map of the North Sea near Hook of Holland (from INT Admiralty Chart 1472 - Bathymetric map of the North Sea near Hook of Holland by the Hydrographer of the Royal Netherlands Navy at Den Haag. Copyright 2019 by Netherlands Ministry of Defence.).

Bathymetric maps give the sea bed level with respect to a reference level, the Chart Datum (CD), generally the Lowest Astronomical Tide (LAT). The sea bed level is presented in meters below CD, thus indicating a water depth that will never be lower as a result of astronomical tides, hence relevant to mariners sailing in shallow water. Note that CD/LAT is not necessarily the lowest sea level, as meteorological and oceanographic effects may cause a further set-down. Also note that tides vary around the world, so that CD is not a horizontal plane.

In areas without any tidal influence, CD is referenced differently, often as Mean Sea Level (MSL). Admiralty Charts in the Baltic Sea, for instance, are referenced to MSL. Through additional low water level analysis, a low water level needs to be established against which port water area design depths are referenced.

Contrastingly, terrestrial (topographic) surveys use a different reference level, such as MSL, or a local ordnance level such as Normal Amsterdam Level (NAP), depending on the country. This may lead to confusion, as illustrated in Figure 2.16.

Most bathymetric and topographic maps are not freely available, but have to be bought. Open source data exists, for instance GEBCO (https://www.gebco.net), but these may not have the required accuracy and reliability for nearshore port planning. For more recent and reliable bathymetric data, surveys need to be performed in an early stage of the development process. Bathymetric surveys are usually made with vessel-mounted equipment that measures the depth ("single beam") or a sweep of the sea bed ("multi-beam"). Nowadays, topography and nearshore bathymetry are also measured with airborne systems using Lidar technology and satellites. The depth of penetration into water, however, is limited depending on transparency.

It should be noted that in very dynamic coastal systems, the bathymetry is not static and a morphodynamic assessment should be undertaken. Water depths may also vary between seasons as a result of siltation and erosion due to varying storminess and river discharges.

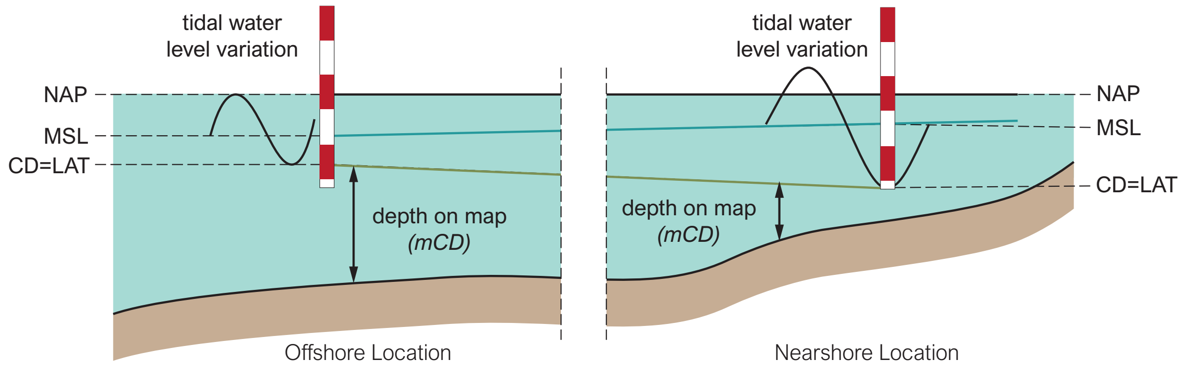


Figure 2.16: Different reference levels may give rise to confusion (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

2.4.3 Metocean conditions

Metocean conditions refer to the magnitude and frequency (or probability) of occurrence of wind, waves, currents, water levels, and climate conditions such as temperature, rainfall and fog. Metocean conditions are important for designing the port layout, port infrastructure and terminal equipment, and in particular:

- vessel response to waves, currents and wind when
  - entering and leaving the port, and
  - at berth;
- downtime of the port, due to adverse weather conditions;
- design of coastal structures such as breakwaters and equipment on terminals to withstand extreme weather conditions;
- sedimentation of access channels; and
- impact of manmade structures on the adjacent coastline.

In the early stages of development metocean conditions are usually derived from published databases (open source or commercial) and site surveys. In the later design stages, this is often combined with hydrodynamic modelling and statistical analysis to estimate conditions during extreme events.

In the following subsections we further discuss the following types of metocean conditions: water levels, wind, waves, currents, other metocean conditions and climate change.

For further reading see also:

- CIRIA; CUR; CETMEF (2007) – "The Rock Manual. The use of rock in hydraulic engineering (2^{nd} edition)"
- PIANC (2012b) – PIANC Report N°117 "Use of Hydro/Meteo Information for Port Access and Operations"

Water Levels

When averaged over sea and swell waves, water levels with respect to a fixed reference level may vary due to:

- tides,
- storm surges,
- low barometric pressure, e.g. during hurricanes,
- large-scale meteorological and oceanographic effects, such as El Niño,
- tsunamis, and
- sea level rise.

These phenomena take place on a wide range of timescales, meaning that the water level is actually never at rest. A port design has to take these variations into account:

- in the reclamation height of terminal terrains and the deck level of structures, and
- in the available water depth in port water areas, if necessary in combination with a tidal window.

When designing port structures or defining terminal terrain levels, the magnitude and joint frequency of water level variations originating from tides, waves, storm surge and long term sea level variations need to be taken into account (see Figure 2.17 for an example).

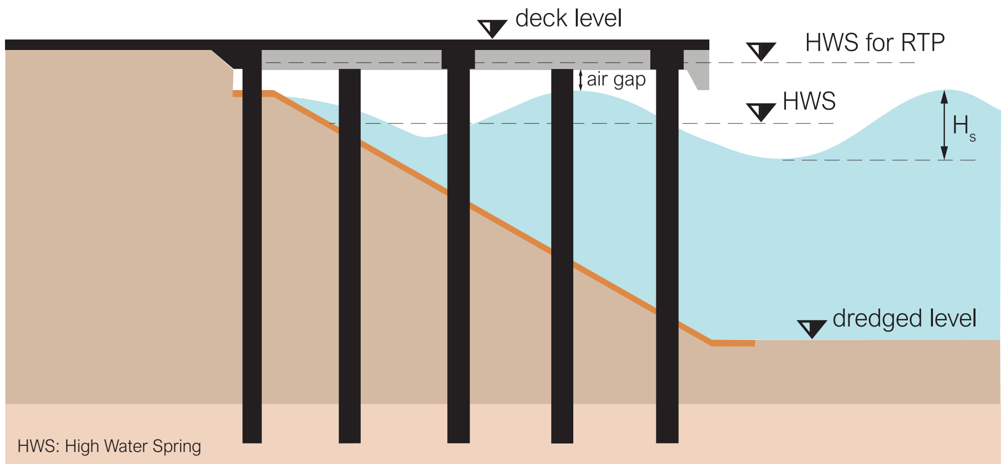


Figure 2.17: Quay deck level and probability of occurrence of the water level (RTP = return period, the inverse of the probability of occurrence) (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Tides Tidal water level variations are often the most prominent in ports. If a tidal window is considered (see Part III – Section 4.2.2), the duration and frequency of high waters needs to be known in detail. Due to astronomical effects, tides vary not only during the month (neap-spring cycle), but also at longer timescales (e.g. the 18.6 year nodal cycle). Tables of astronomical tides can be derived from Admiralty Tide Tables (Figure 2.18), or from published databases such as IHO (www.IHO.org) or Deltares (blueearthdata.org). These tables provide detailed local tidal information. Operational use, however, requires information on tides including metocean effects, which can only obtained from daily reports via internet.

Storm surges Extreme wind set-up and barometric pressure changes can yield nearshore water levels much higher than the highest tide. A port design has to take the probability of such extreme events into consideration, in areas with extreme tropical storms, but also in more moderate climate zones. A statistical analysis, supported by hydrodynamic modelling, is often necessary.

Tidal Levels referred to Datum of Soundings

Place	Lat N	Long E	Heights in metres above datum			
			MHWS	MHWN	MLWN	MLWS
Pussur River Entrance	21°48′	89°28′	2·8	2·1	1·2	0·6
Tiger Point	21 51	89 50	3·0	2·2	1·3	0·6
Dhulasar	21 51	90 15	2·8	2·1	1·3	0·6
Rabnabad Channel (Patua)	22 04	90 22	3·0	2·5	1·6	1·0
Hatia Bar	22 29	90 57	4·1	3·1	1·5	0·5
Sandwip Island	22 30	91 25	6·0	4·4	2·1	0·7
Norman's Point	22 11	91 49	4·2	3·1	1·5	0·4
Chittagong	22 20	91 50	4·4	3·2	1·5	0·7
Kutubdia Island	21 52	91 50	3·8	2·7	1·4	0·3
Cox's Bazar	21 26	91 59	3·5	2·6	1·4	0·5
Saint Martin's Island	20 37	92 19	3·2	2·3	1·3	0·5

These levels vary with the season; being about 0.4m lower in March and about 0.4m higher in August. See Admiralty Tide Tables, Volume 3.

Figure 2.18: High and low water levels during spring and neap tide as derived from Admiralty Charts (from INT Admiralty Chart 7425 - MALANCHA RIVER TO ELEPHANT POINT by the Bangladesh Navy Hydrographic & Oceanographic Centre. Copyright 2017 by Bangladesh Navy.).

Low barometric pressure In the eye of a tropical storm the barometric pressure, hence the air pressure at the sea surface, is very low. This pulls up the sea level and this 'mountain' of water travels with they eye of the storm. When it reaches shallow water, however, its propagation speeds decreases and its height increases. Combined with the storm surge at one side of the storm, this can lead to extremely high water levels. Hurricane Katrina, that struck the state of Florida in 2005, for instance, made landfall with a surge up to 8 m high.

Large-scale meteorological and oceanographic effects Water levels along major ocean basins often show seasonal variations as a result of large-scale effects, such as El Niño (oceanographic) or the North-Atlantic Oscillation (atmospheric). As a result, there can be differences in average water levels between seasons of up to 1 m. These effects are not presented on Admiralty Charts. Surveys during various seasons are required to identify these 'residual' effects.

Tsunamis Tsunamis may cause significant damage to ports, if it were only because these are located close to the shore, with their quays not high above mean sea level. Ports in tsunami-prone areas therefore need to consider the impact in their design and operation. Critical or vulnerable terminal areas or industries behind the quay may need to be located on elevated terrain or further inland to reduce their vulnerability. Breakwater designs may have to incorporate tsunami effects. At the operational level, vessels may need to leave berth and the port in advance of a tsunami (Figure 2.19). To that end, a tsunami warning system should be in place.

For further reading see also:

- PIANC (2010) – PIANC Report N°112 "Mitigation of Tsunami Disasters in Ports"

Figure 2.19: Effect of the 2011 tsunami on a Japanese port (Port of Ishinomaki by U.S. Air Force photo/Staff Sgt. Robin Stanchak is licenced under CC0 1.0).

Sea Level rise Port structures are typically designed for a lifetime of 50 years and therefore sea level rise needs to be taken into consideration. Intergovernmental Panel on Climate Change (IPCC) (see www.ipcc.ch) publishes regular updates of the most recent scenarios for eustatic (or the global average) level rise. For some areas, regional sea level rise estimates are available. They can often be found through national meteorological institutes (e.g. KNMI in the Netherlands or NOAA in the US). Especially in deltaic areas with a soft subsoil, the important information for port design is relative sea level rise, that is the combination of eustatic sea level rise and subsidence. Information on subsidence rates can often be obtained with the local geological survey service (e.g. TNO in the Netherlands, or USGS in the US).

Wind

Knowledge of wind speed, direction and duration are relevant for:

- access channel orientation for vessel entrance and departure;
- access channel width;
- mooring forces and vessel motions at berth;
- port layout development and orientation of berths; vessels with a large air draft such as container, cruise or woodchip vessels are sensitive to wind forces;
- port zoning; dust emitting operations, such as a coal terminal, are often located downwind of sensitive operations, such as a container terminal, and residential areas; and
- design of structures and terminal equipment:
  - wind forces on a vessel increase mooring line forces,
  - wind loads on high Ship-To-Shore (STS) container quay cranes can cause a high stresses in crane beams, and
  - the height of container stacks may need to be limited under high wind conditions.

It is no news that tropical storms come with high wind speeds. In tropical areas, however, there are also so-called 'squalls', short-lived high wind speed events associated with thunder storms or pressure fronts.

Wind data is often presented as an average speed (m/s, kn, Bft), an average direction (i.e. SSE) and speed extremes (e.g. for 3 sec gusts or 1-minute averaged). Figure 2.20 (left) provides an example of a wind rose, which is a common way to show how wind speed and direction are distributed at a particular location.

Wind data are available from published sources (EMWCF, NOAA or local weather institutes) or measured by meteo stations during a survey campaign. Extreme wind speeds are either derived through statistical analysis of long-term data records or by a dedicated analysis of tropical storms (hurricanes, cyclones, typhoons; Figure 2.20 (right)).

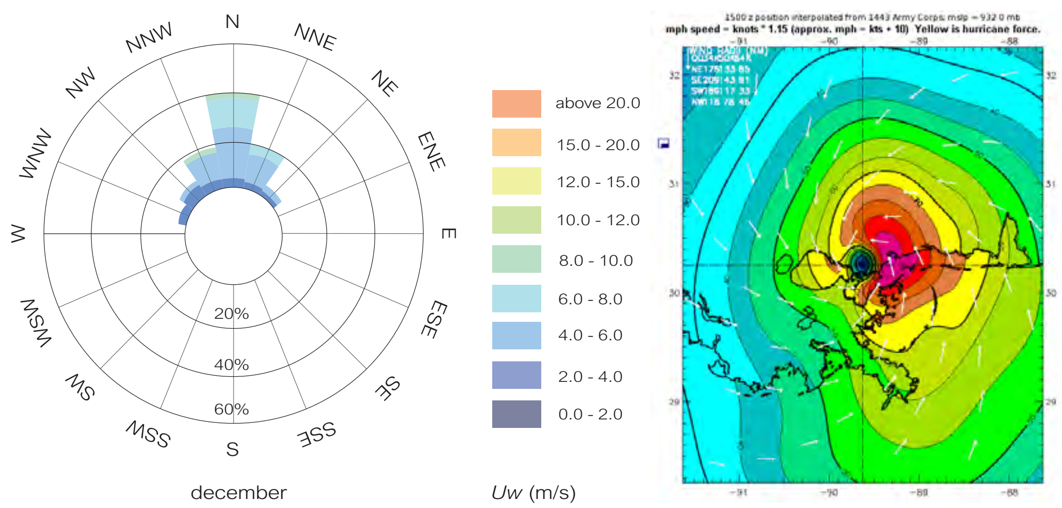


Figure 2.20: Left: example of a wind rose (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0); right: Hurricane wind speeds during landfall of Hurricane Katrina (by NOAA is licenced under CC0 1.0).

Waves

Wave penetration is often the main cause of (unexpected) downtime of ports. Protection of port basins from wave action to allow for safe and efficient port operations is therefore a key element in port layout development. As this can lead to substantial investment costs, knowledge of the local wave conditions is important for:

- planning and design of the access channel orientation, to facilitate vessel entrance and departure,
- mooring forces and vessel motions at berth, and
- design and planning of structures, especially breakwaters.

Gravity waves (sea and swell waves), infragravity waves and seiches (Figure 2.21) are all important, as the natural frequency of vessel motions is of the same order of magnitude as the frequencies of these wave types.

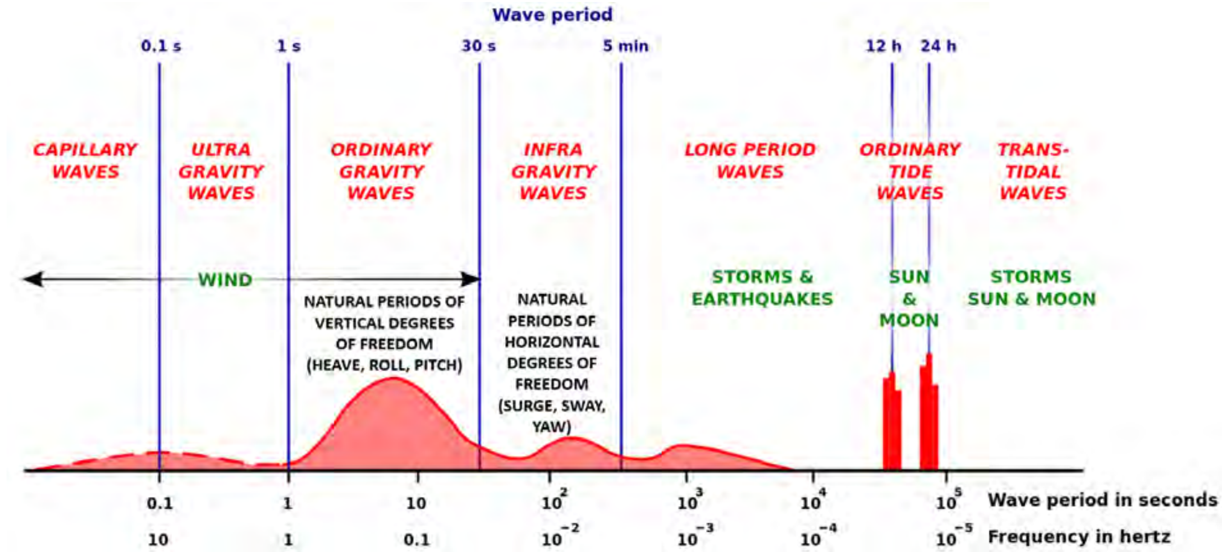


Figure 2.21: Wave periods and eigen periods of vessel motions at berth (adapted from Munk ICCE 1950 by Walter H. Munk is licenced under CC BY-SA 3.0).

Gravity waves A distinction is usually made between sea and swell waves. Sea waves are short-crested, steep and more chaotic and have been generated by the local wind. Swell waves are long-crested, smooth and long-period, and they have propagated from a distant storm (see, for instance Holthuijsen, 2010). PIANC (2014d) gives a definition of swell waves (Tp > 10 s) and sea waves (Tp < 10 s). A vessel's response to sea waves is different from that to swell waves (also see Part III – Section 4.2.2).

Infragravity waves Infragravity waves have a longer period than gravity waves, in the order of 20 - 600 s. Especially longer vessels are very sensitive to these waves, even if the wave height is small, e.g. 10 - 25 cm. Infragravity waves are formed by complex nearshore processes, and although there are certain indicators to determine whether they occur at a site, they cannot be easily seen by the naked eye and therefore measurements are required. Infragravity waves may cause resonant surges in a port basin, which is problematic for sensitive cargo transfer operations such as container transfer. As vessel lengths increase, more ports experience downtime as a result of this phenomenon. Hence there is a growing emphasis on taking infragravity waves into account in the design and layout of ports.

Seiches A seiche occurs in an enclosed body of water with reflecting boundaries, such as port basins, lakes and water bodies enclosed by manmade structures. Seiches can be caused by a sudden change in wind speed or atmospheric pressure, creating a wave which may continue to oscillate back and forth for hours. In the case of port basins, they may also be triggered by low-frequency waves at sea, which enter the basin and resonate there (De Jong and Battjes, 2004).

Currents

Knowledge on currents is relevant for:

- planning and design of the access channel orientation, to facilitate vessel entrance and departure,
- width of access channels, since cross currents influence steerability
- the required depth of the access channel,
- mooring forces and vessel motions at berth, especially in rivers, and
- sedimentation and erosion processes.

Currents can have a variety of causes, such as large-scale oceanic circulations, tides, river discharge, wave breaking and wind. At a particular site the specific conditions determine which of these is dominant. Some Admiralty Charts provide information on peak currents in a port entrance. Understanding the nature of the currents and their variations at a site requires surveys and possibly also hydrodynamic modelling. Modelling is definitely needed for extrapolation to extreme conditions and to predict the effects of the new port on the currents in the area.

Other meteorological conditions

Not every port is located in a moderate climate zone. Issues under more extreme climatic conditions can be dense fog, snow and ice (drift ice, river ice, solid ice, atmospheric ice). PIANC (2019c) states: '... ice and snow may play a role in site selection, as they may significantly impact the design of port structures (to resist ice loads) and/or the operational availability of the port or terminal. Other factors, including fog, rain and atmospheric ice, should be considered if they would have a significant operational impact on the planned facility.'

Climate Change

Climate change is an issue in port development and operation. Figure 2.22 gives an overview of possible impacts of climate change on port development and operations. The most visible effect is a rising sea level that needs to be taken into consideration in the design of structures and the terminal height (which is very difficult and costly to modify later). Increasing storminess results in higher wind speeds and more extreme waves. Climate change mitigation measures will probably result in an energy transition less dependent on fossil fuel. This will have a significant impact on cargo flows in and out of port.

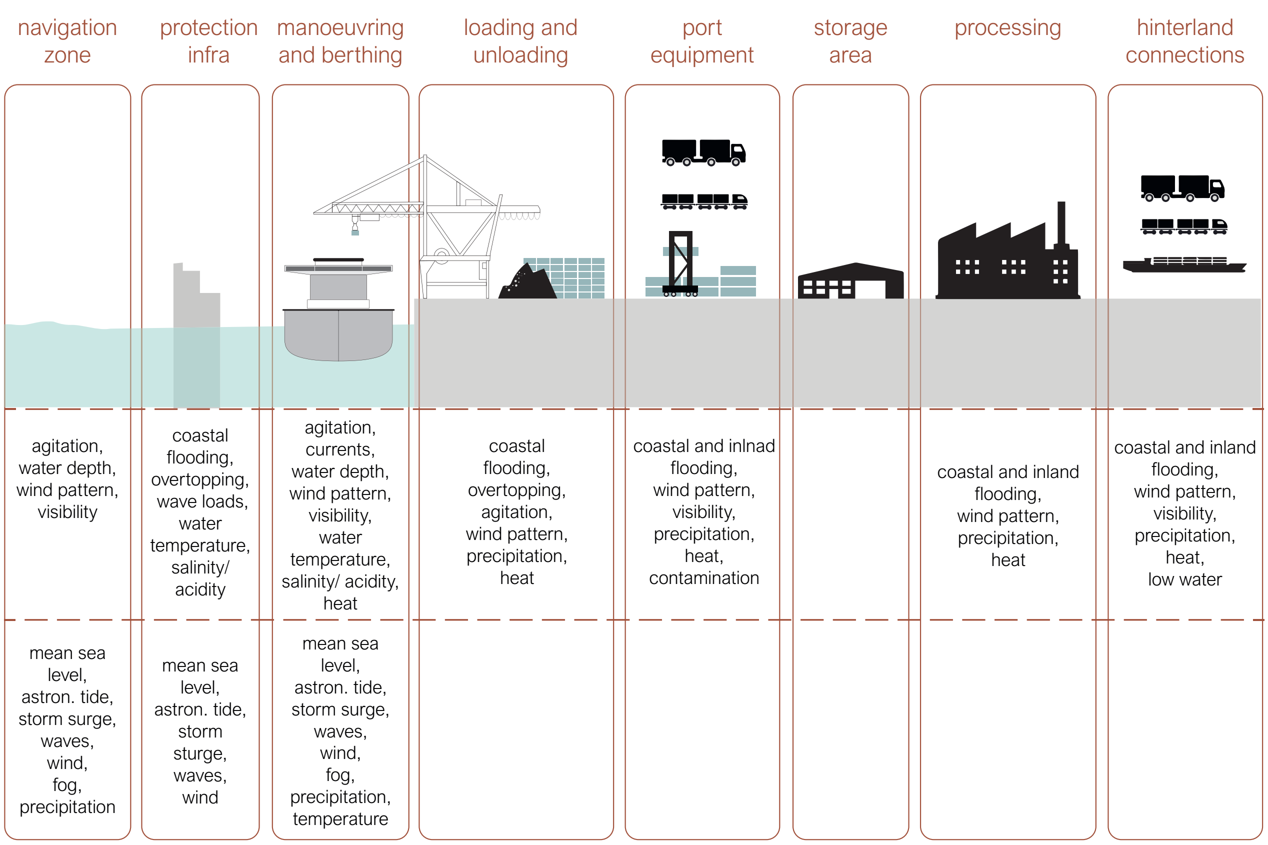


Figure 2.22: Impact of climate change on port development and operations (modified from PIANC, 2019a, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

2.4.4 Geotechnical conditions

Subsoil and bed characteristics are important for the design of structures and dredging schemes, respectively. Breakwater costs can easily double if subsoil conditions are not favourable. Dredging costs of a rocky subsoil can exceed those of a soft sediment bed by a factor 10 or more. Uncertainty about subsoil conditions translates into a risk of structural failure or worse (see, for instance, the video of the destruction of the port of Chibatao, Manaus, Brazil by liquefaction of the subsoil) and the impact this has on operations and safety. Therefore, geotechnical surveys need to be carried out. In deltaic areas they will include cone penetration tests, borings, sea bed sampling, subsidence rates, etc. In mountainous terrain also slope stability is also an issue, in case of marine canyons even under water.

For further reading see also:

- ISSMGE (2005) – “Geotechnical and geophysical investigations for offshore and nearshore developments”
- PIANC (2016a) – PIANC Report N°144 “Classification of Soils and Rocks for the Maritime Dredging Process”

2.4.5 Seismic conditions

In areas where earthquakes occur frequently, port site selection and structural design are strongly influenced by the possibility of seismic activity. Ground accelerations during earthquakes results in forces on structures (Figure 2.23). In addition, earthquakes may induce liquefaction, due to which the subsoil loses its strength. Moreover, submarine earthquakes may generate devastating tsunamis (see ‘Tsunamis’ on page 81). Peak ground accelerations and the risk of liquefaction are studied in dedicated seismic hazard studies.

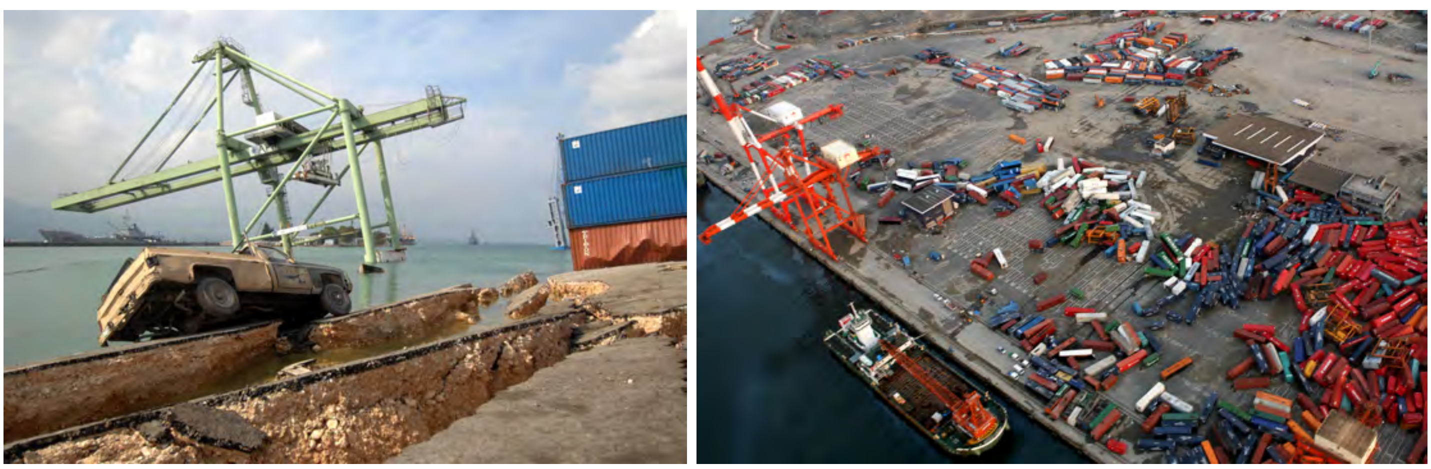


Figure 2.23: Earthquake effects on ports. Left: Collapsed gantry crane, Port au Prince, 2010 (by Chief Mass Communication Specialist D. C. Pearson (U.S. Navy) is licenced under CC0 1.0); right: Earthquake damage at container terminal, Port of Sendai, Japan, 2011 (by Cpl. M. Angel (U.S. Marine Corps) is licenced under CC0 1.0).

2.4.6 Sedimentation and erosion

Changes in wave, current and sediment transport patterns generally give rise to sedimentation and erosion. This can be a dynamic process which occurs naturally, but can also be a result of manmade structures.

Basically, there are four mechanisms that can cause port sedimentation:

1. deposition of suspended sand transported by wave-driven and tidal currents; this sand settles down when reaching the sheltered port access area (Figure 2.24, left);
2. longshore sand transport bypassing the updrift breakwater (Figure 2.24, left and right); the breakwater blocks the longshore transport, so the transport sand piles up there and the coastline comes forward; this

goes on until the tip of the breakwater lies in the surf zone and sand starts being transported around it (bypassing); downstream of the breakwater, the opposite occurs: coastal erosion (Figure 2.24, right);

3. import of suspended fine sediment by the flood current (Figure 2.25, right, near the left-hand breakwater) which settles in the quiet waters of the entrance channel and the port basins, and
4. import of sediment by density currents driven by high suspended sediment concentrations (Figure 2.25, right, through the entire entrance).

Figure 2.24: Left: Harbour siltation, Oluvil Port, Sri Lanka; right: updrift accretion, downdrift erosion, Port of Nouakchott, Mauretania. Images from Sentinel-2 cloudless by EOX IT Services GmbH are licensed under CC BY 4.0.

The former two effects are strongest on sandy coasts with high wave activity under large angles of incidence, the latter two occur mainly in areas with high turbidity levels in the coastal zone (Figure 2.25, left).

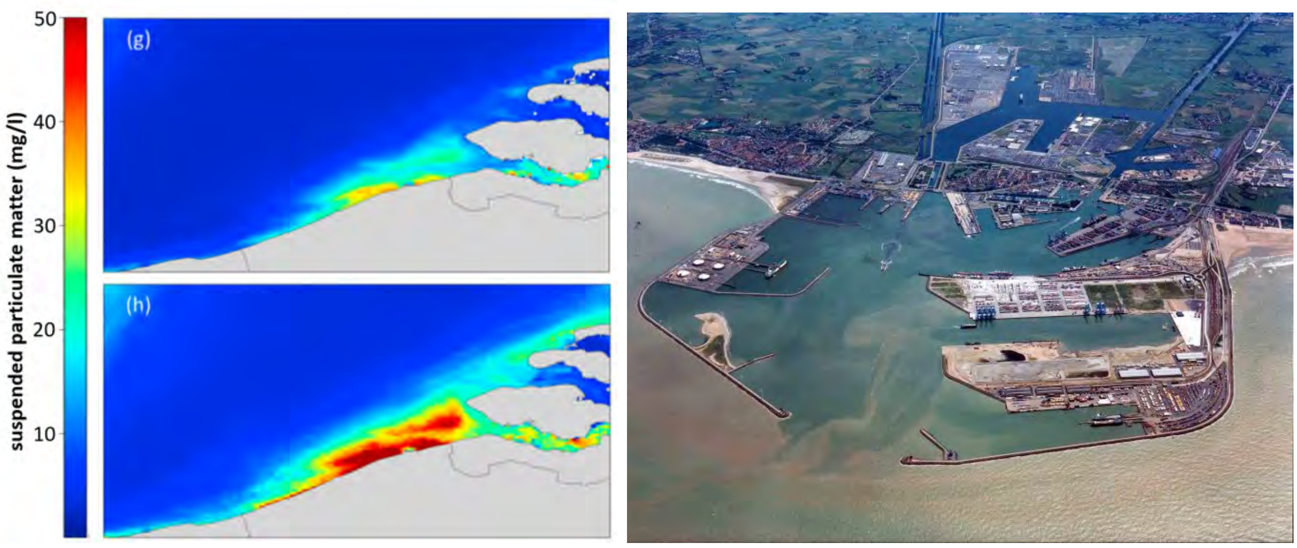


Figure 2.25: Left: observed summer (g) and winter (h) turbidity maxima around the mouth of the Western Scheldt (by Van Maren et al., 2020, is licenced under CC BY 4.0); right: suspended sediment entering the port of Zeebrugge (Port of Bruges-Zeebrugge by antikrot is licenced under CC BY-SA 3.0).

Sand deposition and siltation also occur in inland ports, especially river ports. Coarse sediment transported along the river bed can enter a port access channel and be deposited there. Fine suspended sediment may also be carried into the port by currents associated with water level variations, or in the case of flood-exposed water bodies by settling from overbank flood flow.

There are quite some examples of ports which have been taken out of operation due to excessive siltation of the entrance. The extent of erosion and siltation can be investigated in morphological studies, often supported by numerical models. The layout of the port entrance can be designed to mitigate siltation, but usually maintenance dredging cannot be avoided. The costs involved can be a significant part of the OPerational EXpenditures (OPEX) of a port.

For further reading see also:

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

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.

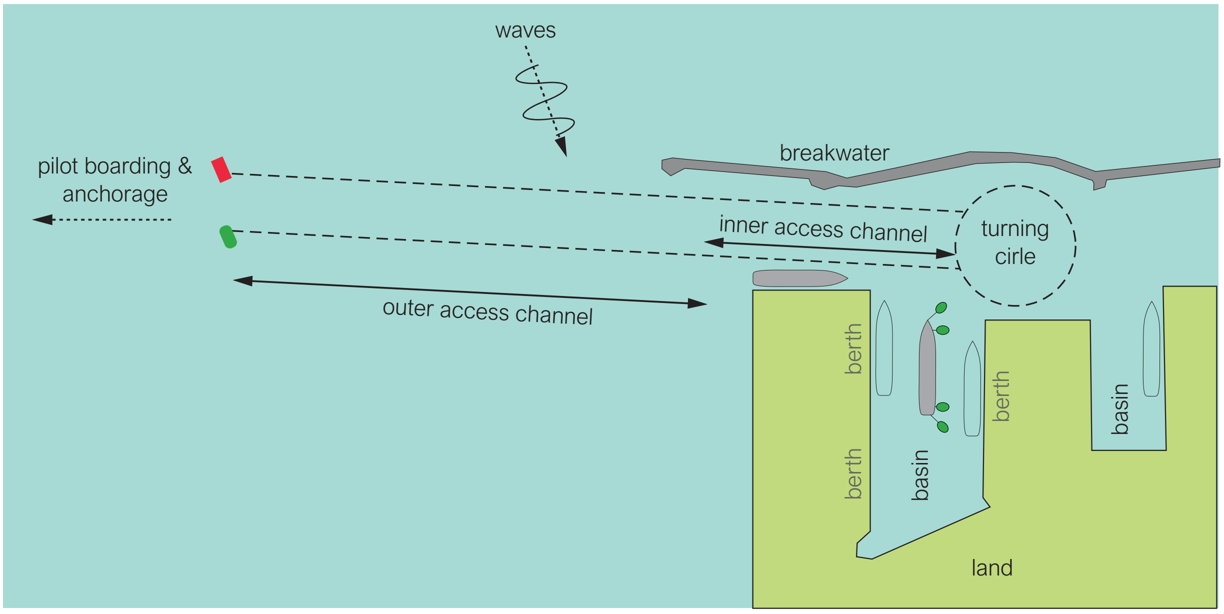


Figure 3.1: Port water areas; pilot boarding and anchorage are further offshore (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

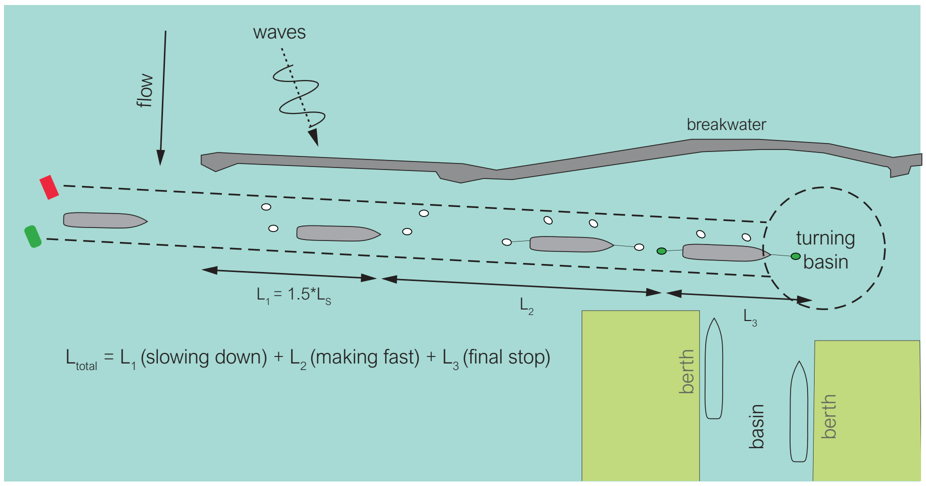


Figure 3.3: Deceleration and stopping procedure upon port entrance (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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):

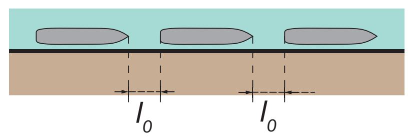
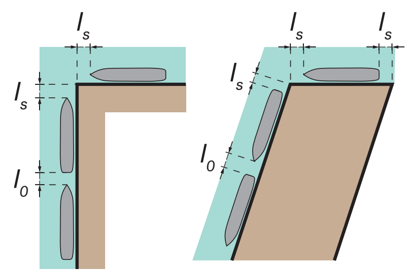
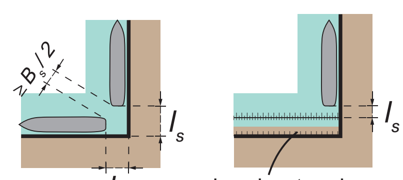
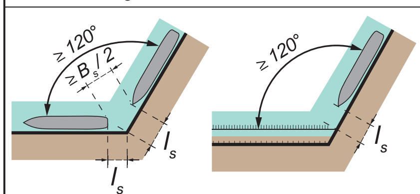
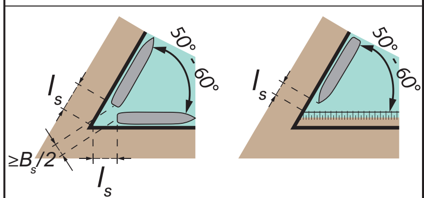
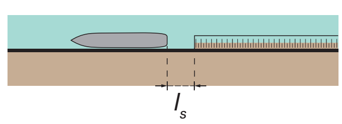
Dock Layout	Recommended distance between berths				
	L_s > 300m	201 - 300	151 - 200	100 - 150	< 100
	l_0 = 30m	25	20	15	10
	l_s = 30m	25	20	10	5
	l_s = 45m	30	25	20	15
	l_s = 30m	20	15	15	10
	l_s = 60m	50	40	30	20
	l_s = 20m	15	15	10	10

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).

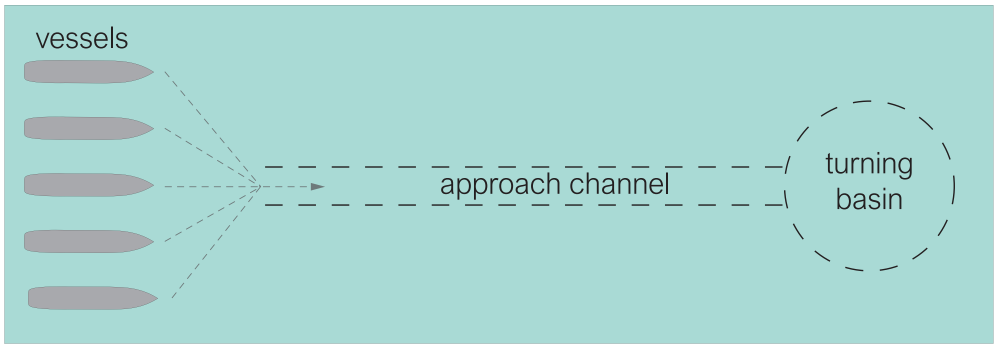


Figure 3.4: Port approach system considered as a service system in queueing theory (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

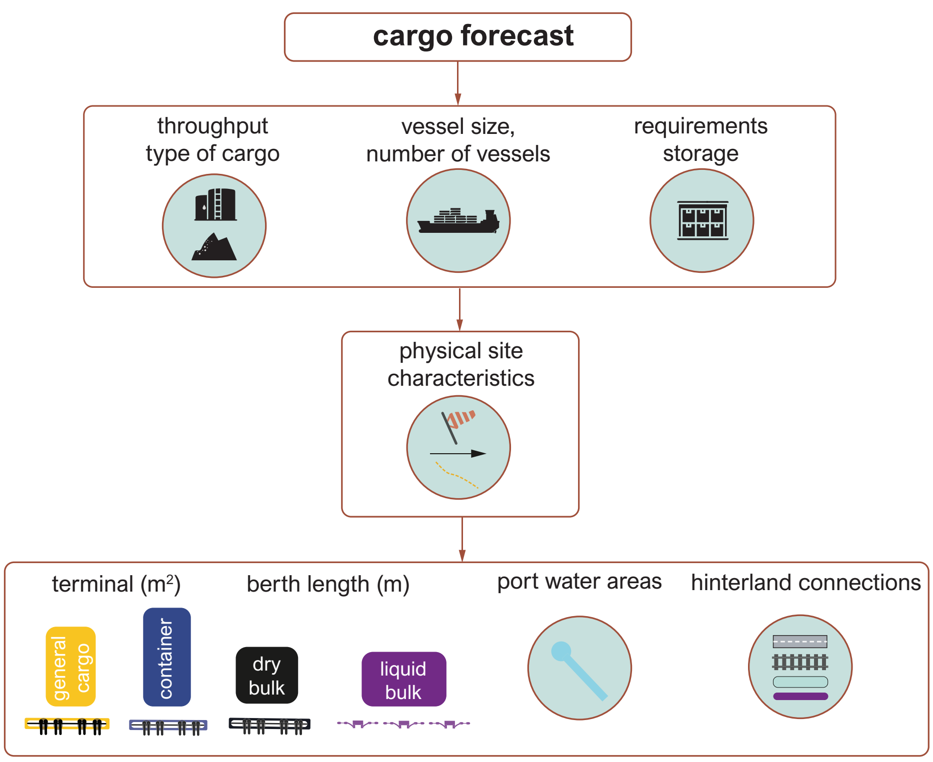


Figure 3.5: Schematic of port layout development (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

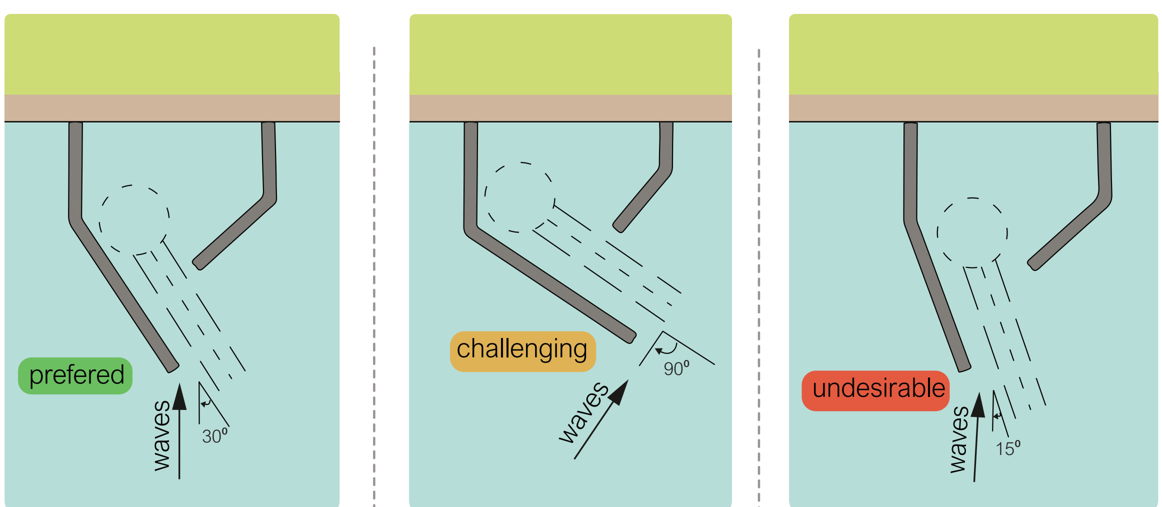


Figure 3.7: Access channel orientation, balancing vessel hindrance and wave penetration (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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).

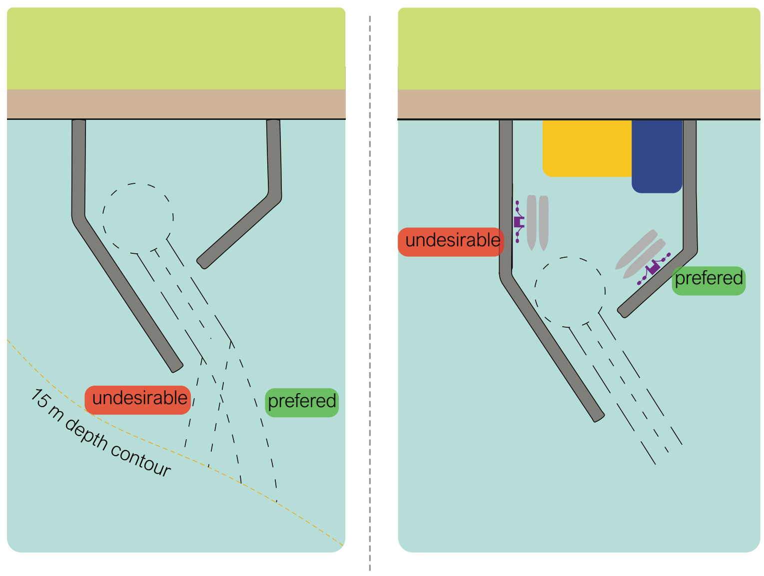


Figure 3.8: Left: curved access channel; right: free stopping range (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

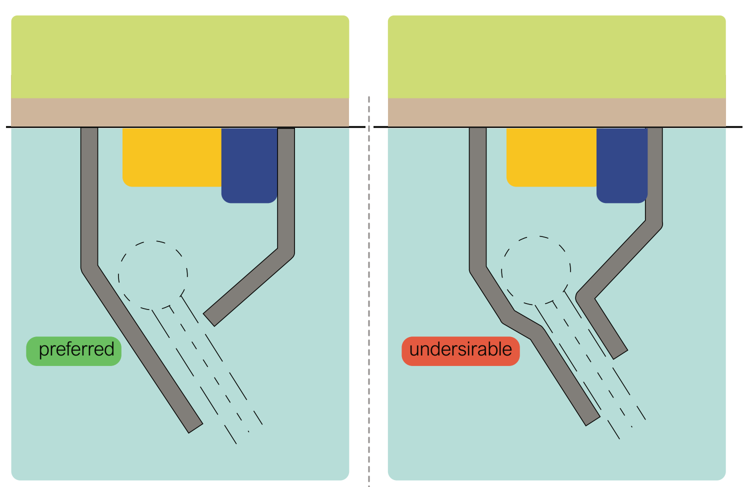


Figure 3.9: Distance of breakwaters to the access channel (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

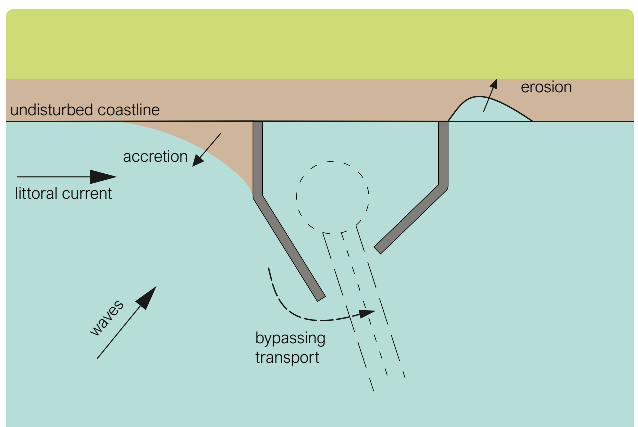


Figure 3.11: Sediment bypassing a breakwater (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

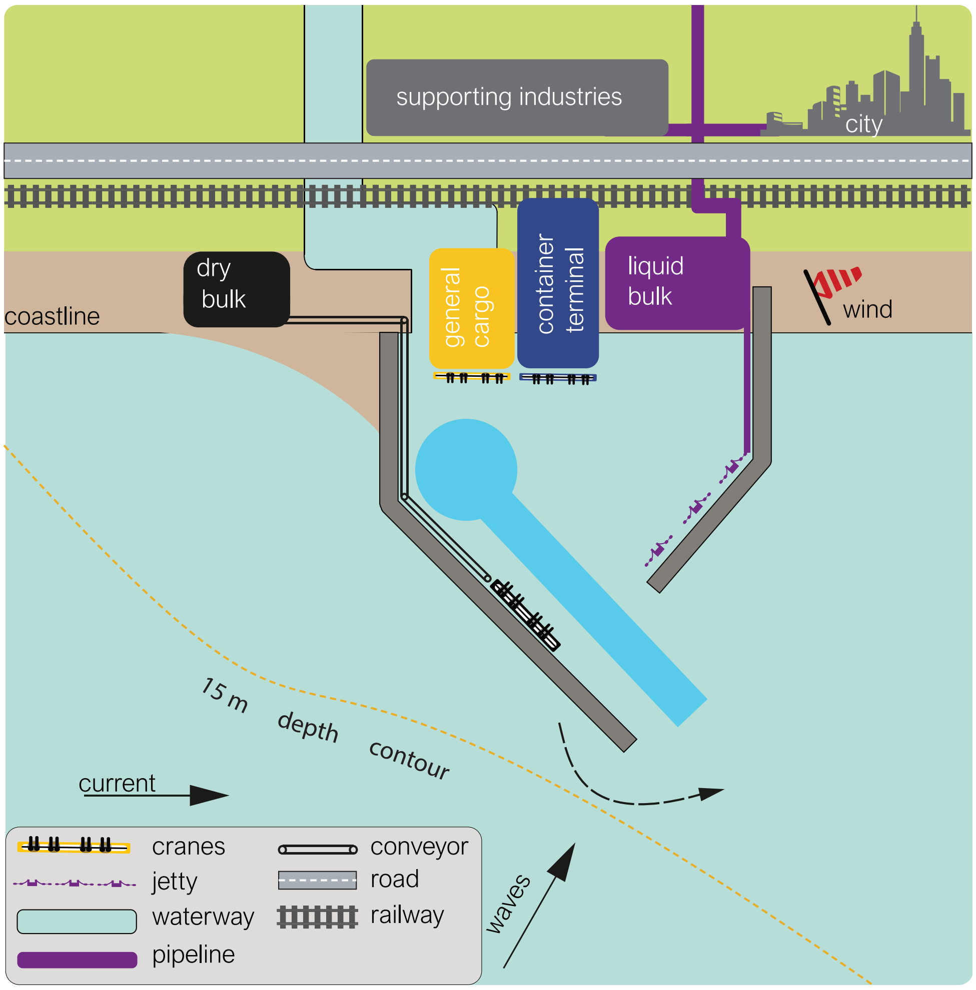


Figure 3.12: Conceptual port layout (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

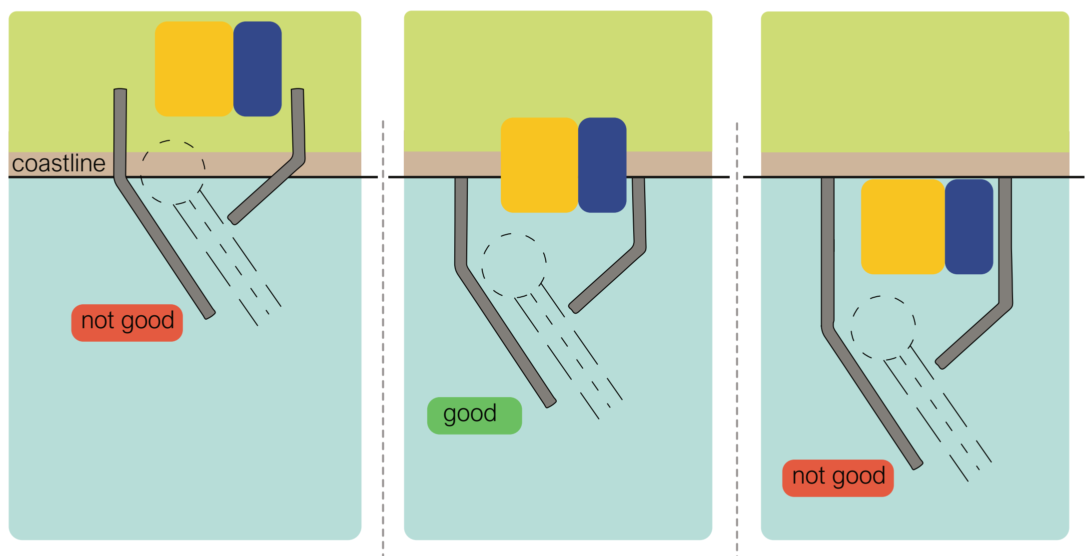


Figure 3.13: Cut-fill balance (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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 %	0.1310	0.0235	0.0062	0.0019	0.0007	0.0002	0.0001	0.0000
40 %	0.2355	0.0576	0.0205	0.0085	0.0039	0.0019	0.0009	0.0005
50 %	0.3904	0.1181	0.0523	0.0532	0.0142	0.0082	0.0050	0.0031
60 %	0.6306	0.2222	0.1103	0.0639	0.0400	0.0265	0.0182	0.0128
70 %	1.0391	0.4125	0.2275	0.1441	0.0988	0.0712	0.0532	0.0407
80 %	1.8653	0.8300	0.4600	0.3300	0.2300	0.1900	0.1400	0.1200
90 %	4.3590	2.0000	1.2000	0.9200	0.6500	0.5700	0.4400	0.4000

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.

Iteration	**Action**	**Configuration**			**(Un)mooring**	**(Un)loading time**	**Occupancy (%)**	**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:

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

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

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

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).

4 Container terminals

4.1 Backgrounds of container transport

4.1.1 Historic development

[1]After World War II world trade increased rapidly and sea transport along with it. This led to serious congestion in ports and long waiting times. Until that time, most of the goods used to be shipped in the form of general cargo (Figure 4.1), which was time consuming and labour intensive.

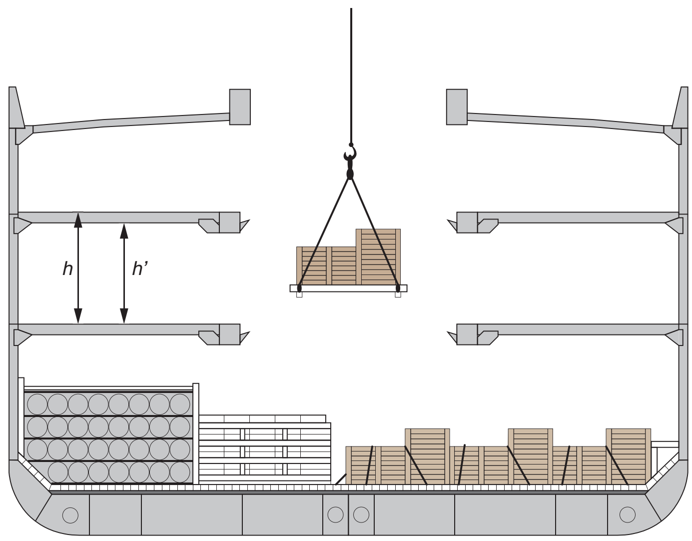


Figure 4.1: General cargo vessel loading and unloading; left: Longshoremen unloading cargo from a freighter by handtruck (by Asahel Curtis is licenced under CC0 1.0); right: a cross section of a general cargo vessel (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The container had been introduced in the fifties as a standard size box for transport of cargo by truck and rail across the USA. Its use in sea transport followed after some time and reduced turnaround and waiting time in ports substantially (Van Beemen, 2008). In 1955 the White Pass & Yukon Route started operating a fully intermodal service between the Canadian mainland (Vancouver) and Alaska (Skagway). For this purpose a specially built container vessel was used, with a capacity of 4,000 tons or 600 containers.

Malcolm McLean (Figure 4.2) is generally regarded as the godfather of containerisation. His initiatives led more or less to the global application we know today. In 1955 he bought a shipping line (known as Sealand, later taken over by Maersk) and started maritime container transport. In the sixties, McLean's engineers developed technology to further speed up container handling, such as the corner casting, the twist lock, the spreader and the first container gantry crane.

In the sixties parties involved in container shipping finally agreed on a standard for the ISO container. The smallest early ISO container had dimensions of 8 ft x 8 ft x 20 ft (2.44 x 2.44 x 6.10 m^3). This explains why the capacity of a vessel or a container storage yard is still expressed in Twenty Feet Equivalent Units (TEU). Nowadays forty feet long containers are used besides the twenty feet ones, and additional standard sizes for length, width and height have been introduced.

At the end of the sixties, Sealand operated 36 container vessels and 27,000 containers and offered services to 30 ports worldwide. Initially limited to coastal shipping along the US West and East Coast, the first Sealand

[1]This chapter made use of the handout 'Container terminals' (Quist and Wijdeven, 2014) for the Ports and Waterway courses CIE4330 & CIE5306 at TU Delft

Figure 4.2: Malcolm McLean at railing, Port Elizabeth, mid-1960s (by Maersk Line is licenced under CC BY-SA 2.0).

containers arrived in Rotterdam in 1966. Following Sealand's success, many other shipping companies entered the container business. Over the past 45 years container shipping has boomed and spread across the globe, taking over a major share of general cargo transport (Van Beemen, 2008). Figure 4.3 shows how the world container throughput at ports has evolved over the last 50 years. The effect of the 2008 economic crisis is clearly visible, and so will the effect of the 2020 pandemic be.

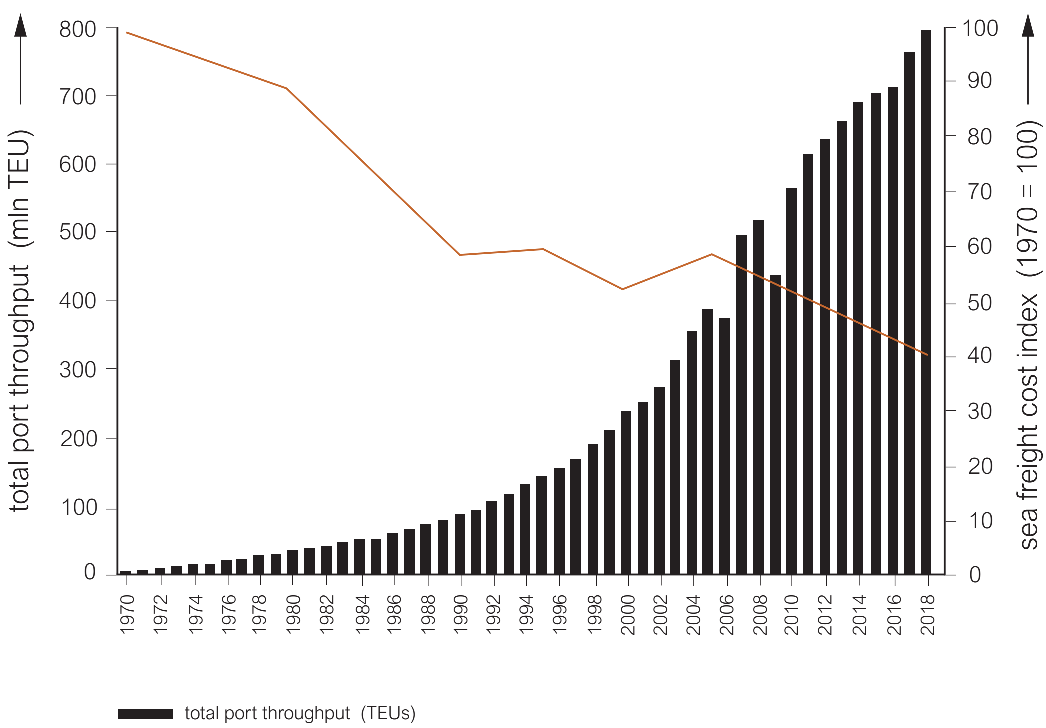


Figure 4.3: Evolution of world container port throughput and sea freight price index (source throughput until 2009: Global Networks; source throughput 2010-2018: UNCTAD; source freight price: Dr. Jean-Paul Rodrigue, Dept. of Global Studies & Geography, Hofstra University, New York, USA, image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

A similar development has taken place in inland waterborne container transport, where the Netherlands have played a leading role (Figure 4.4).

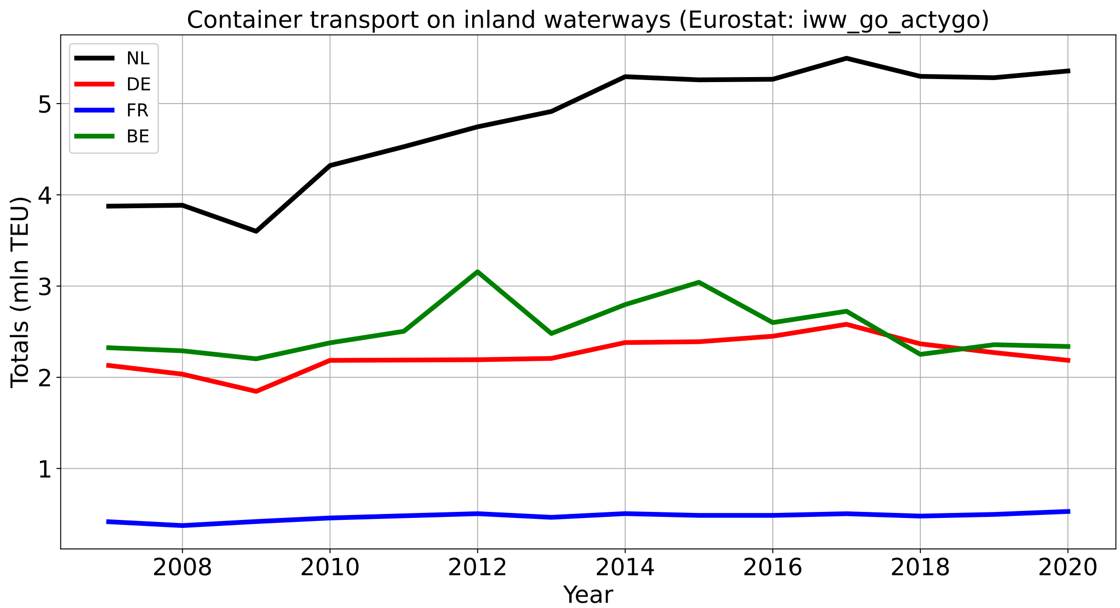


Figure 4.4: Evolution of inland container transport in Europe (source: Eurostat – iww_go_actygo; image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Containerisation has contributed to significant changes in the global structure of manufacturing and production, and vice versa. Low-cost production has been moved to South-East Asia, India, Central America and Eastern Europe, which required a global transport network and has indeed led to a greater share of the world's production being transported worldwide (also see Part I – Chapter 1). Consequently, shipping lines have grown substantially in terms of geographical coverage, frequency of services and transit times. Mutual competition has driven them to an economy of scale approach, both in vessel size and organizational structure, which has brought down the costs per TEU significantly (Figure 4.5).

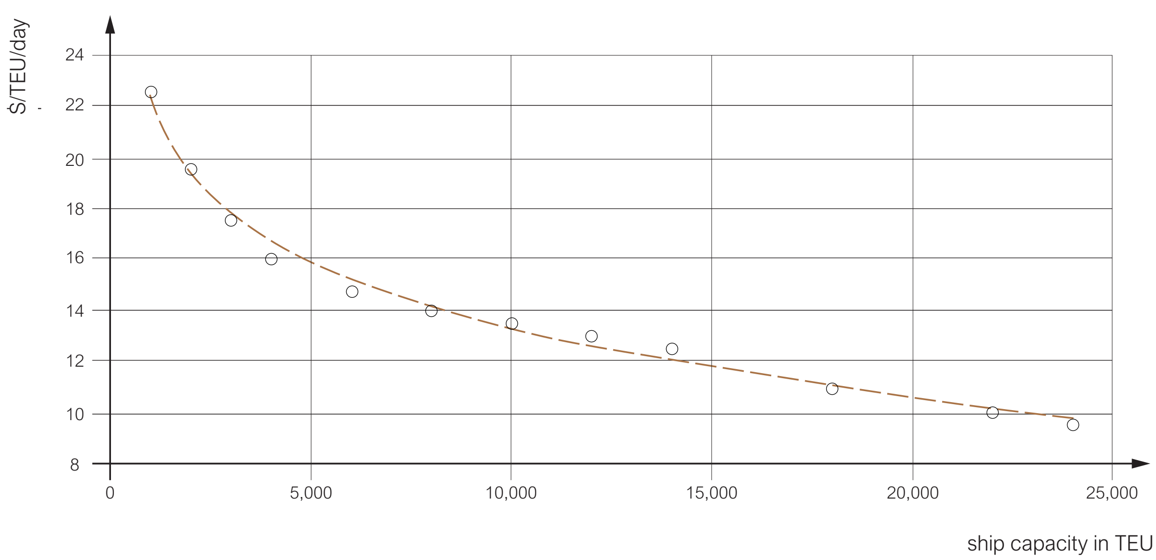


Figure 4.5: Daily operating expenses for container ships per TEU (reworked from https://transportgeography.org by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

4.1.2 Major transport routes

The drive to cost reduction not only led to larger ships, but also to investment sharing and round-the-world services. Ships call at different terminals during a trip, thus ensuring efficient use of their capacity. The two major traffic routes are the Europe – Far East route and the Trans Pacific – North route (Figure 4.6).

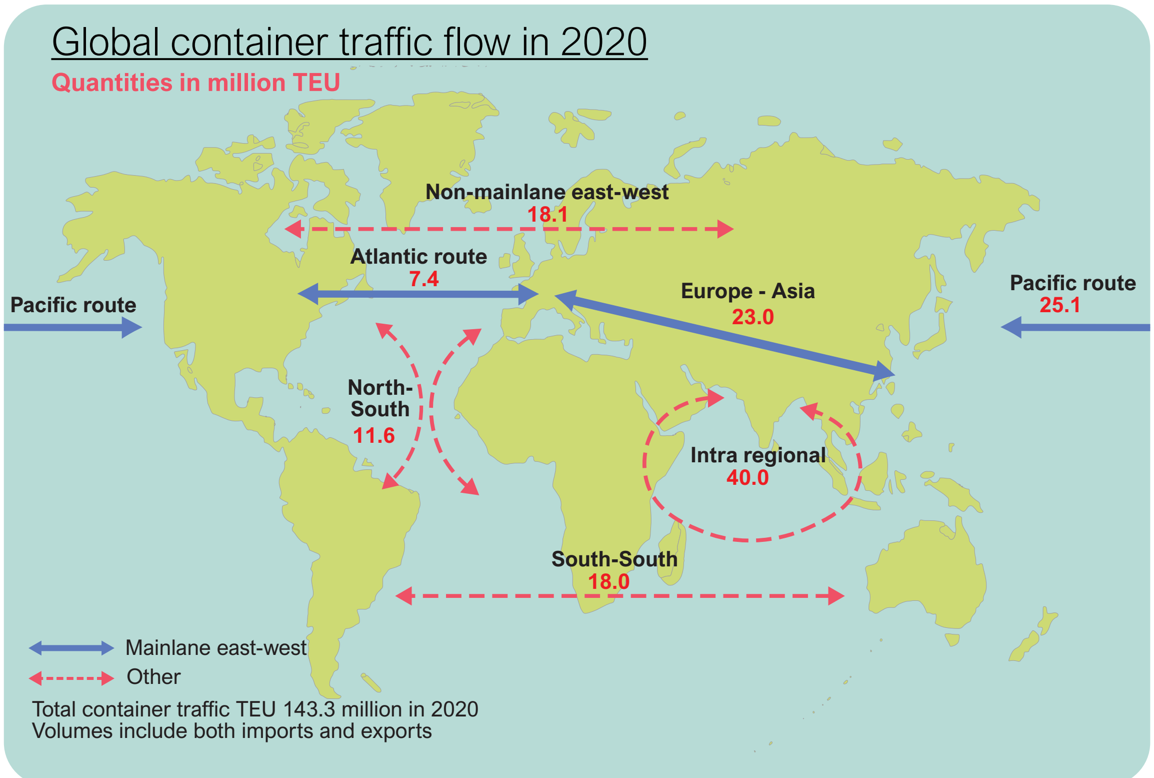


Figure 4.6: Major global container traffic flows, 2020 (source: UNCTAD, 2020, image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

As an example, Figure 4.7 shows a detailed west- and eastbound schedule for Asia - Northern Europe. The transit time from Shanghai to Rotterdam is 33 days.

Figure 4.7: Example of a ship's schedule on the Mediterranean-Asia route (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 4.8 gives another example, of the Transpacific-North route between China and the US-west coast. The transit time from Shanghai to Long Beach is 14 days.

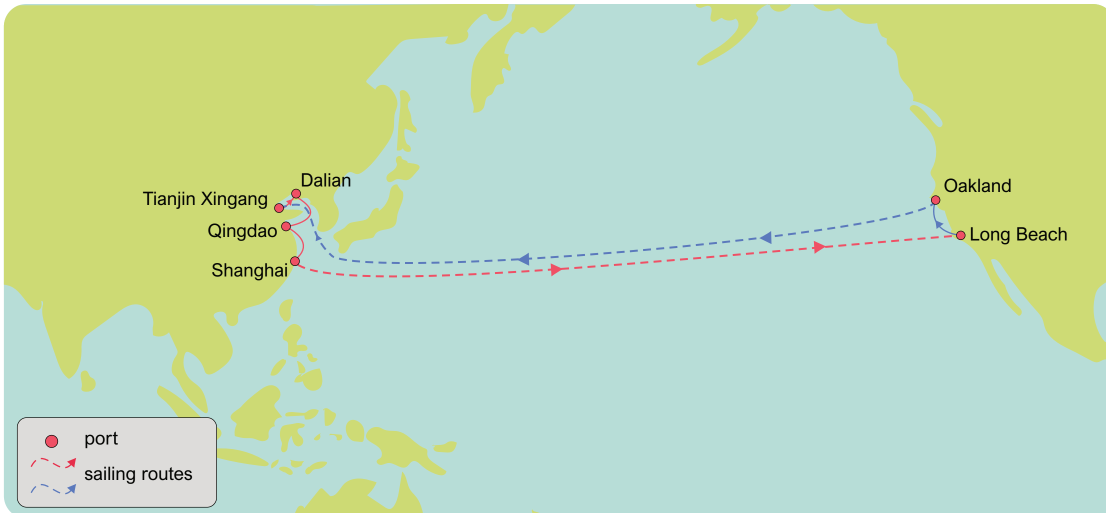


Figure 4.8: Example of a ship's schedule between China and the US west coast (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 4.9 shows a third example, from the Transpacific-North route between China and the US-west coast via the Panama Canal. The transit time between Shanghai and New York is 28 days.

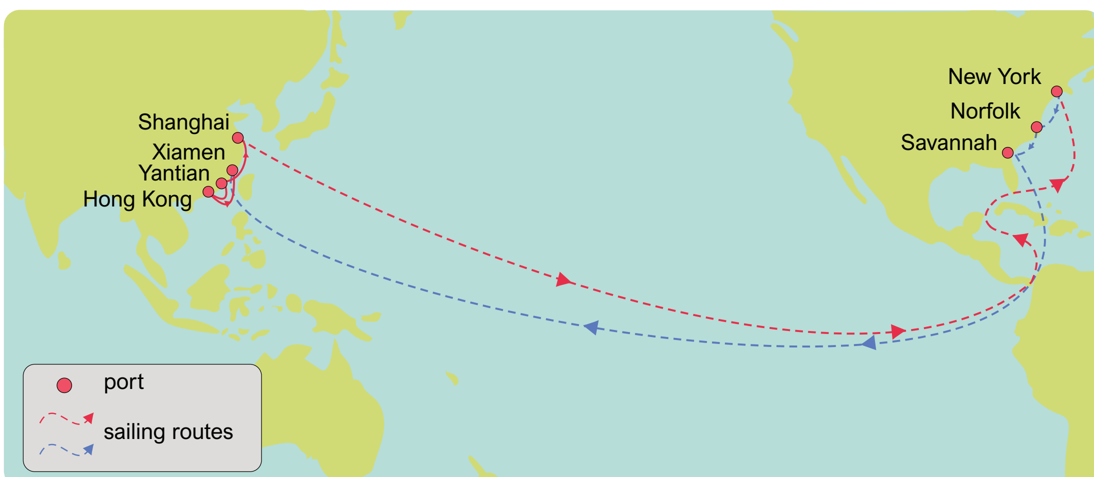


Figure 4.9: Schedule China – US east coast (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

4.1.3 Pros and cons

The worldwide shift to containerisation of almost all general cargo required enormous investments, which were only possible because of great advantages, such as (Van Beemen, 2008):

- *Labour saving* – up to 30 tons of containerised cargo can be discharged or loaded in a minute, by a crew of two to three people. Thanks to containerisation, labour intensive ad costly transfer of boxes, crates, drums, bags, sacks and bales from one mode of transport to another can be avoided.
- *Economies of scale* – for general cargo, larger vessels and larger port facilities were no solution, as loading and discharge time were already disproportionally high compared to actual sailing time and cost. Containerisation

brought the technical solutions and standardisation that enabled scale increase and cost reduction.

- *Time saving* – with containerisation, unloading and loading times of vessels, trains and trucks were reduced considerably. A large container vessel spends 24 hours in port, a much smaller conventional general cargo vessel several days.
- *More transport options* – world-wide container transport infrastructure enables shippers to develop long and complex transport chains that are fast, reliable and economical.
- *Security and damage reduction* – Because a container is packed only once, more attention can be paid to packing it properly, with knowledge of the product.
- *Safety* – general cargo stevedoring was hard, dirty and dangerous work. Container handling is generally a safer activity, although accidents still happen.
- *Cost saving* – cost saving continues with the ongoing scale increase in container transport (see Figure 4.5).

There are also disadvantages, however:

- *High investment cost* – well-equipped container infrastructure requires high investment. For the poorest nations it is difficult to raise the capital required for government-owned container terminals. Hence those countries do not get access to low-cost and efficient transport of goods, which hampers economic development and investment possibilities. Large global terminal operators are now breaching this vicious circle by increasingly investing in terminal facilities in developing countries.
- *Empties* – it is not always possible to find export cargo nearby for an unpacked import container. The empty container must then be stored or transported to a location where export cargo is available, which involves costs without direct revenue. About 20% of the total global port moves are empties. Because the dwell time for empties is higher than for loaded containers, the percentage of empties stored on terminals is often considerably higher. There is a lot of idle capital tied up in empty containers and there is also the cost of storing empties on expensive land close to the quay side. Efficient repositioning of empties can therefore make the difference between a loss or a profit for the shipping line.
- *Labour* – Because of containerisation the large general cargo stevedoring companies in the developed world have all gone, and in some developing countries this process is still ongoing. As a result a huge workforce got unemployed and only part of them could be absorbed by the new container terminals.
- *Theft* – theft in ports used to be widespread, though the scale of individual cases was mostly limited. Because of containerisation, theft in ports now concerns entire containers and is the domain of organised crime.
- *Smuggling* – smuggling of contraband, especially drugs, is a persistent problem in container ports, despite sophisticated detection technology. This, too, is the domain of organised crime, as is trafficking.
- *Security* – Customs have deployed high tech solutions such as X-ray scanning. Yet, experts are concerned that international terrorism may use container infrastructure for terrorist attacks.

Figure 4.10: ISO container dimensions (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

4.2 Container types and container vessels

4.2.1 Container types, sizes and demands

The International Standards Organisation (ISO) issued the official standard dimensions of containers (Figure 4.10):

- The most common standard is the TEU, which is a container with L_c = 20 ft (6.10 m), B_c =8 ft (2.44 m) and H_c = 8 ft 6 inches (2.60 m). Its own weight is about 24 kN. Its internal volume is approximately 32 m^3 and the maximum "payload" amounts to 220 kN. This implies that the container cannot be filled to the limit with high density cargo. In practice the payload is much lower even, on average around 100 kN;
- The forty feet container (2 TEU or 1 Forty Feet Equivalent Units (FEU)) measures twice as long and has the same width and height as the 20 ft container. Its own weight is about 45 kN and the internal volume measures 65 m^3. The maximum payload is only marginally higher than the TEU: 270 kN, but the average payload in practice is 175 kN.

There are several other container types in use, including:

- Oversize containers (longer than 40 ft) (of which in particular the 45 ft is used more often);
- High Cube containers (height 9 ft 6 inches, 2.90 m);
- Over width containers (wider than 8 ft). (Pallet wide containers, often 45 ft in length).

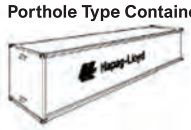
Standard container 	20 ft, 40 ft and 40 ft High-Cube Version Standard container with full steel box top, bottom and sides and end doors
Hardtop Container 	20 ft, 40 ft and 40 ft High-Cube Version Standard container with a removable steel roof. Used for heavy or tall cargoes – with loading from the top or side
Ventilated Container 	20 ft Especially for cargo which needs to be ventilated.
Refrigerated Container 	20 ft, 40 ft and 40 ft High-Cube Version The cooling is provided via a built-in electrically driven unit. Power is supplied either through power grids on board or ashore, or by "clipon" diesel generators during land transport.
Porthole Type Container 	20 ft and 40 ft This container does not have a built in cooling unit. The cooling is provided through openings (port holes) either by the ship's refrigeration system, a land terminal or by a 'clip-on' refrigeration unit during land transit.
Open-Top-Container 	20 ft and 40 ft Provided with removable tarpaulin. Especially for over-height cargo. Loading from the top or side.
Flatrack 	20 ft, 40 ft and 40 ft High-Cube Version Especially for heavy loads and wide loads.
Platform 	20 ft and 40 ft Especially for heavy loads and oversized cargo.
Tank Container 	20 ft For the transport of liquids including foodstuffs, for example: petrochemical products, alcohol, fruit juices, edible oils, food additives.

Table 4.1: Container types (modified from PIANC, 2014b, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0)

The latter category originally measures 8 ft 2.5 inches (2.50 m), because that width allowed placing two Euro pallets side-by-side inside the container. Moreover, it is the maximum width permitted on the Western European roads. Since this has been relaxed to 2.60 m, the container width of 8 ft 6 inches has become more common.

As can be expected, the use of non-ISO containers gives complications, hence extra costs:

- On the vessel the cell guides in the holds are designed to receive ISO containers. Hence Oversize and Overwidth containers have to be placed on deck, which limits the flexibility of the loading schedule.
- On the terminal the Oversize containers, also known as OOG need their own stacks, which again limits flexibility.
- The "spreader", the frame used under the crane trolley or by the yard equipment to pick up a container by the four twist locks at the corners, must be adjustable to accommodate the different lengths (20, 30, 40 or 45 ft) and widths.
- For the onward transport of containers by road or rail different lengths require special provisions on the trailer or rail wagon to fasten the containers at the corner castings.

Apart from the variation in size there is a range of special purpose containers (see Table 4.1).

Dry ISO containers are used for general purpose transportation. The cargo is loaded via doors at the end of the container. These totally enclosed, box-type containers are also called dry vans.

Thermal or insulated ISO containers are used to transport chilled and frozen goods. They are also used for temperature sensitive products. These containers have insulated walls but they don't have a refrigeration unit.

Refrigerated ISO containers (reefers) are used when a steady temperature must be maintained during transport. They are the same as insulated containers but have a built-in refrigeration unit. Reefers require electricity supply, both on the vessel and on the terminal. In case reefers are stacked in multiple layers, reefer racks are provided (Figure 4.11).

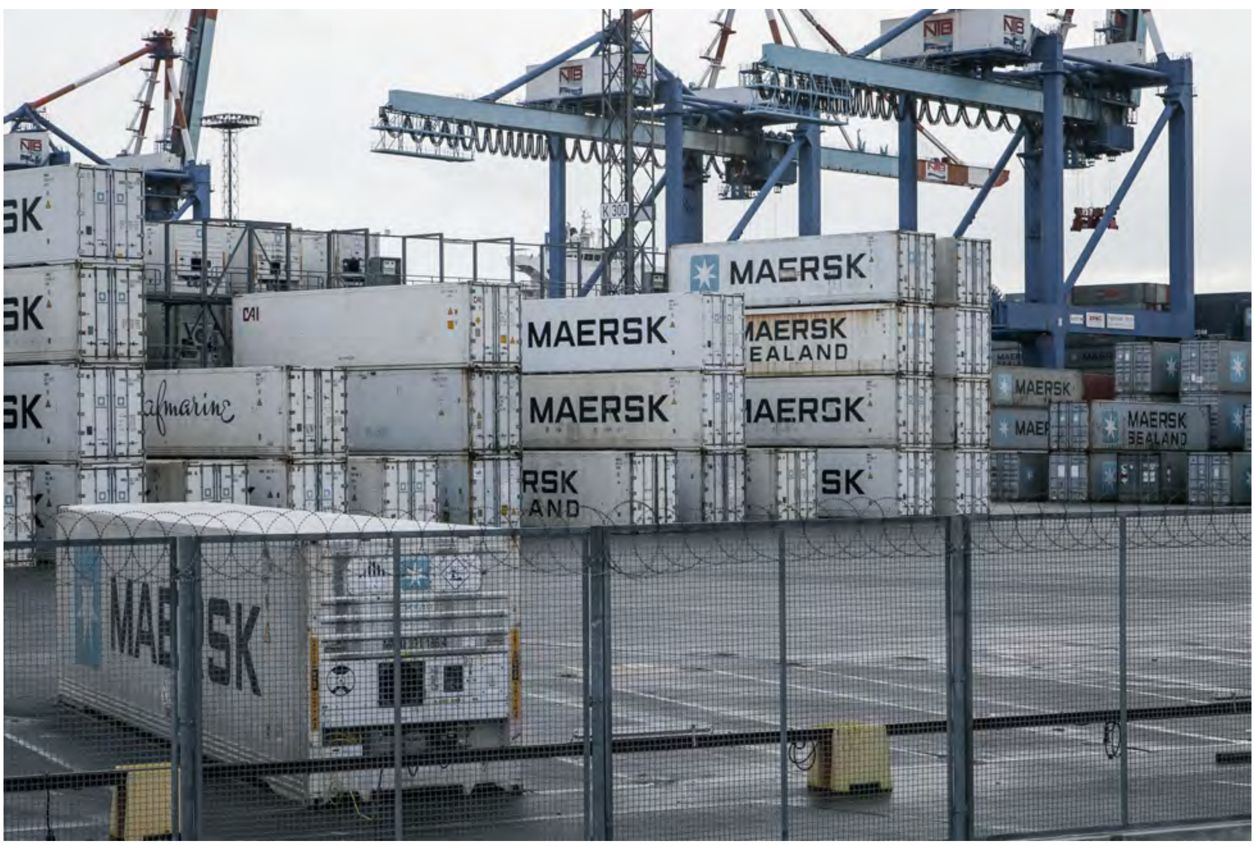


Figure 4.11: Reefer racks in a container storage (by Stefan Georgi is licenced under CC BY-NC-SA 2.0).

Flat racks and platforms are used to transport heavy machinery. They have no side walls, but may have end bulkheads. There are also collapsible flat rack containers. These are open-sided containers with end bulkheads that can be folded down when the rack is empty.

Open top containers are used to transport heavy, tall or hard-to-load cargo, and bulk material, such as coal or grain. These box-type containers with no top can be loaded from the top or from the end.

Tank type containers are used to transport liquid or bulk materials. They have a cylindrical tank mounted within a rectangular steel framework, with the same overall dimensions as other intermodal containers. Heated tank containers are used for wax, for instance.

4.2.2 Container vessels

The "first generation" container vessels were general cargo vessels, converted to carry containers. Since then several classes of container vessels have been built with ever increasing dimensions and capacities (Table 4.2, Figure 4.12 and Figure 4.13).

Vessel class	**TEU-capacity**	**DWT-range**	L_s	D_s	B_s
1^{st} generation	750 – 1,100	14,000	180 – 200	9	27
Feeders	1,500 – 1,800	30,000 – 35,000	225 – 240	11.5	30
Panamax I	2,400 – 3,000	45,000 – 80,000	275 – 300	12.5	32
Panamax II	3,000 – 5,000	80,000 – 100,000	290 – 310	12.5	32.3
Post Panamax	5,000 – 10,000	90,000 – 120,000	270 – 320	12.5 – 16	38 – 42
New Panamax	10,000 – 14,500	120,000 – 150,000	366	15.2	49
ULCV	14,500 – 24,000	157,000 – 235,000	400	15.2 – 16	56 – 61

Table 4.2: Container vessel characteristics (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 4.12: The ULCV MSC Gülsün (23,756 TEU) on its way to the port of Rotterdam (MSC GÜLSÜN by kees torn is licenced under CC BY-SA 2.0).

For port planning purposes the development of the size of container vessels is of great importance. Parties involved are continuously trying to beat competitors by creating the possibility to accommodate vessels bigger than existing ones. Limiting factors in vessel design, such as structural strength, engine capacity, cavitation of propeller and rudder, cargo handling speed and available depth in ports have gradually been resolved. The recently built container vessels enable economies of vessel size due to their large hauling capacity, but diseconomies of scale in their handling capacity (relatively long service times in ports). Hence it makes sense to deploy large vessels at long distance routes (Veldman, 2011).

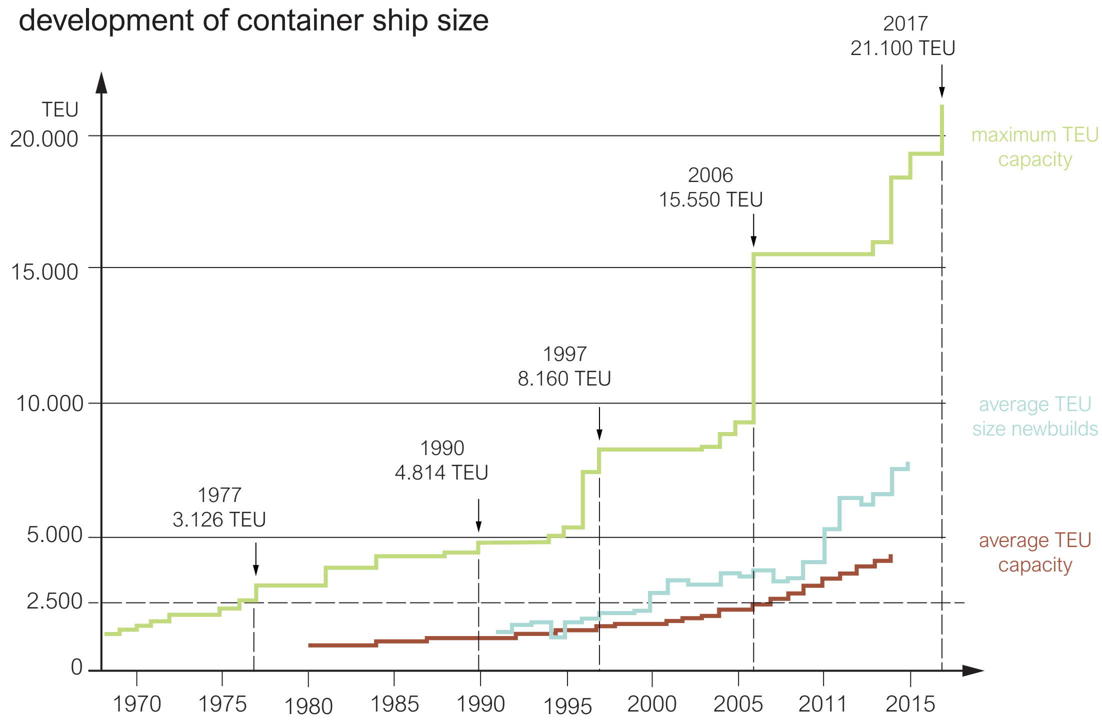


Figure 4.13: Development of container vessel capacities (reworked from Merk, 2018, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

4.2.3 Container flows and modal split

The yearly averaged throughput of containers is key input into planning and design of a container terminal. It is derived from the so-called modal split, which gives gives the (forecasted) numbers of containers entering and leaving the terminal via the sea (main lines, feeder lines and short-sea lines), road, rail and IWT.

As shown in Figure 4.14, there are various flows of containers:

- *The import flow* – discharged from a seagoing vessel and finding its way the hinterland;
- *The export flow* – coming from the hinterland and loaded onto a seagoing vessel;
- *The sea-to-sea flow* – transhipment containers that are discharged from a deep-sea or feeder vessel and loaded again onto another deep-sea or feeder vessel;
- *The land-to-land flow* – mostly empty containers returned to the empty depot and leaving again for reloading with local export products; other containers come in by one landside modality, e.g. truck, and leave by another, e.g. IWT.

Figure 4.14, furthermore, gives a simplified example of a modal split, with arbitrary numbers. The assumption that the flows are balanced per transport mode is clearly a simplification of reality: in most cases there is a distinct imbalance. The throughput figures shown include the empty containers, which normally are singled out, because they may be stacked and handled more economically than loaded containers.

The modal split gives the transport flows in number of containers per unit time (in this case year). This is relevant for the quay length design, because the container crane production is also expressed in number of container (moves) per unit time (hour). The other capacity calculations are therefore also carried out in TEU per unit time. For the capacity of the storage yard the division between 20 ft and 40 ft containers has to be known, because the surface area depends on this. This is taken into account via the TEU-factor:

$$f_{TEU} = \frac{N_{20} + 2N_{40}}{N_{20} + N_{40}} \tag{4.1}$$

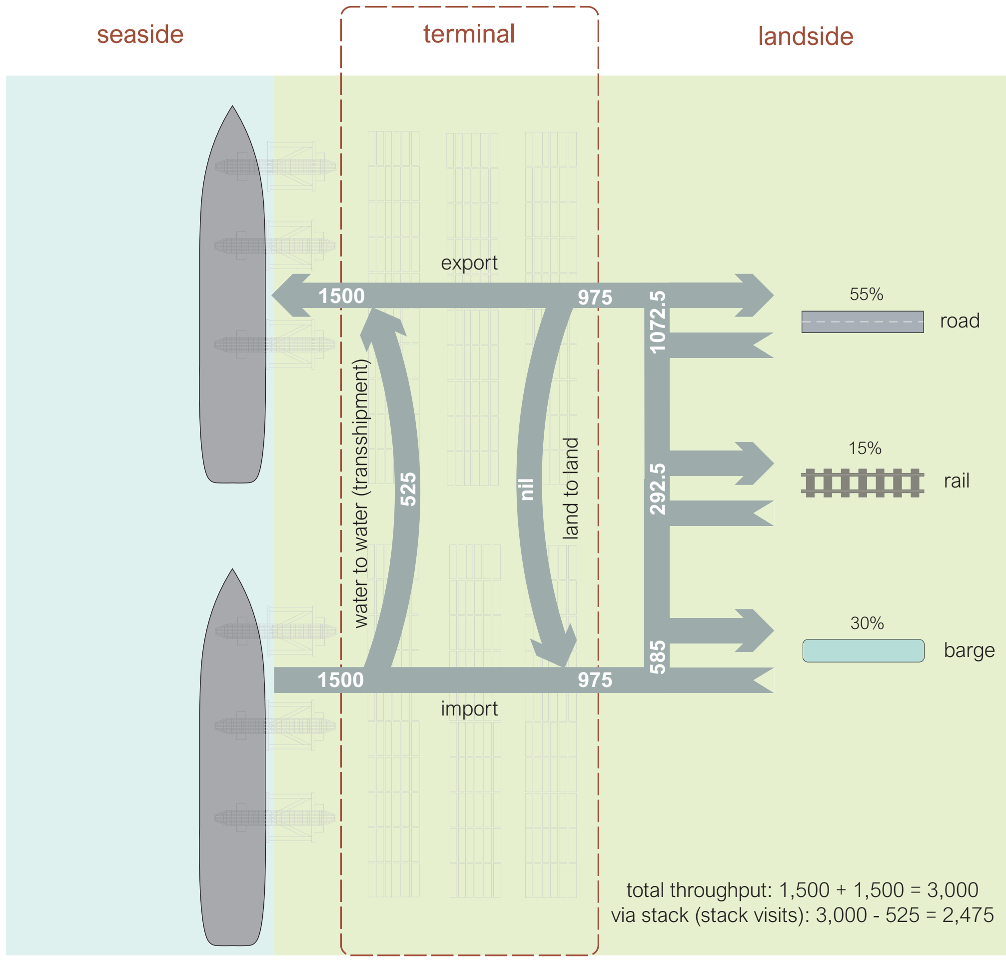


Figure 4.14: Container flows and modal split example (numbers × 1,000 TEU/year) (modified from Quist and Wijdeven, 2014, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

in which N_{20} is the number of TEUs and N_{40} the number of FEUs. This TEU-factor is often characteristic of the type of port and can be derived statistically from data. In developing countries TEU-factors are often low, indicating that a large percentage of goods is transported in 20 ft containers. On the main routes there is a tendency towards 40 ft containers, a trend that is likely to continue for some time.

The initial planning of a container terminal is often based on rules of thumb or relatively simple design formulae, as presented in the subsequent sections, or on a simple form of queuing theory. The final layout may be optimised by means of simulations, which permit to analyse the complete terminal process, including the stochastic processes such as vessel arrivals, crane and other transport equipment availability, and container arrivals/departures via land. Such sophisticated simulation models, however, require precise and reliable input in order to produce reliable results. Also the stochastic character of vessel arrivals is limited nowadays because of tight sailing schedules. Tramp shipping as occurred during the early years of container shipping hardly occurs anymore. As a consequence, scenario-approaches are replacing black-box stochastic approaches.

4.2.4 Terminal archetypes

The relation between the main container flows as described in Section 4.2.3 is the principal determinant of the type of terminal. There are two categories of container terminals, viz.

- gateway terminals, and
- transhipment or hub terminals.

Gateway terminals form the gate to and/or out of a vast hinterland with emphasis on import and export of captive cargo. The most important containers flows are import and/or export. Examples are the ports of Shanghai (China) and Busan (Korea). Import in these gateway terminals consists for a considerable part of empty containers that are being filled with industrial products coming from the hinterland. It can also be the other way around: import mainly consisting of loaded containers and export of empty containers. This is for instance happening in Jeddah (Saudi Arabia) and Kuwait City.

Historically, the hinterland was the determining factor for port site selection. The development of round-the-world services, however, is one of the reasons why specialised transhipment ports have emerged at places without much of a hinterland. Transhipment ports focus on sea to sea flow of containers, rendering landside facilities of less importance. Examples are the ports of Hong Kong (PRC), Singapore, Aden, Salalah (Oman), Dubai and Gioia Tauro (Italy), Algeciras and Valencia (Spain), Malta, Tanger Med (Morocco) and Port Said (Egypt).

Regarding container handling, the Port of Rotterdam is a mix between a gateway and a transhipment port. Rotterdam has a relatively large hinterland and thus attracts a significant volume of gateway containers. That is the reason why the large container carriers deviate from their round-the-world route to call at the Port of Rotterdam. It makes this port also attractive as a container feeder hub for Scandinavia, the Baltic region and part of the United Kingdom.

4.2.5 Forecasting trade and traffic

Trade forecasting is necessary to estimate the demand for traffic, hence for shipping. Traffic forecasting is key to defining the need for terminal facilities. Thus it provides the basis for assessing the viability of a port development project.

Based on trade forecasts in a port's hinterland, traffic forecasts estimate what traffic this could generate through the port, at present and in the future. Traffic forecasts must include transhipment trade and free trade zone goods.

Several techniques may be used, depending on the circumstances:

- For an existing port, it may be sufficient to start with the existing throughput and assume that the traffic will generally grow in proportion to the GDP. This assumes that there are no significant new developments or industries planned in the region which would generate additional specific traffic.
- For a new port or terminal, it may be necessary to conduct interviews with local key industries to ascertain their potential trade and their specific development plans. In order to have a picture of the potential future traffic to the terminal, studying local and regional plans may also be useful.
- In some cases existing general cargo flows may be transferred into containers, which means that rate of containerisation must be estimated in order to have a useful forecast.

It is important to distinguish import/export traffic from transhipment traffic. Import/export traffic is usually the economic foothold of a terminal. Routing the cargo through a different port involves extra costs, so a terminal is generally assured of a certain basic throughput, provided that the facilities keep pace with the demand. Transhipment cargo, however, is easily switched from one port to another if the shipping line manages to negotiate a better deal. Developing a terminal solely on the basis of transhipment is therefore risky.

Container vessel forecasting requires a proper understanding of the nature of the container trade in the region. Maybe local import/export trade will only justify small feeder vessels, or the strategic location of a terminal may rather make it suitable as a global hub for transhipment. In any case the size of container vessels actually deployed in the region serve as a guide to identify the vessel sizes for which the terminal should be designed.

The future development of vessel sizes should also be taken into account, to ensure that access channels, layout, structures and facilities are adaptable if larger vessels need to be accommodated.

Once the "design vessel" dimensions have been defined, all these aspects can be elaborated in further detail. Apart from these design vessel dimensions, the composition of the fleet, the "vessel mix", is an important input to terminal design. The berth configuration and handling capacity required are not a matter of the largest vessel alone, as illustrated by the time-evolution of the average vessel size in Figure 4.13.

4.3 Container terminal operations

Before going into the development of an actual container terminal layout, it is important to understand the logistic process on container terminals. As far as they are relevant to the terminal design, we describe them in this section.

4.3.1 At the quay

Prior to arrival of a vessel the containers to be unloaded have been identified (and those to be loaded have been arranged in the export stack in such a way that they can be transferred to the vessel in the right order).

Immediately after the vessel has made fast at the berth the lashings are taken off the containers above deck and the STS gantry cranes (or portainers) start unloading. A modern STS gantry crane is as high as a cathedral, especially with its booms up. Figure 4.15 presents Post Panamax STS gantry cranes at container terminal Altenwerder in Hamburg (Germany).

Figure 4.15: Post Panamax STS crane at container terminal Altenwerder, Hamburg, Germany (by www.hippopx.com is licenced under CC0 1.0).

These STS cranes are generally rail-mounted. They are characterised by a boom which extends across the moored vessel. This boom can be lifted (Figure 4.16), or pulled inward (when close to airports, for instance). The cranes are provided with a trolley with a spreader, enabling to pick up a container (or two), bring it onto the quay and place it on a transport vehicle that brings it to the storage yard (or vice versa). As container ships were getting larger, STS cranes had to follow in height and reach. At present, the most common STS crane is based on an A-frame with tip-up boom (Figure 4.16). This figure also shows the typical dimensions of an STS crane suitable to handle Super – Post Panamax vessels. Mobile harbour cranes are also used for the loading and unloading of container vessels, mainly small ones.

Some typical properties of STS cranes are:

- *Lifting capacity* – originally 400 kN, now increasing to 800 kN and above, to allow for twin/tandem handling.
- *Outreach* – going up from 30 m for handling Panamax vessels to 70 m for handling Very Large Container Vessels (VLCVs) and Ultra Large Container Vessels (ULCVs).
- *Rail gauge* – varying from 15 to 35 m.

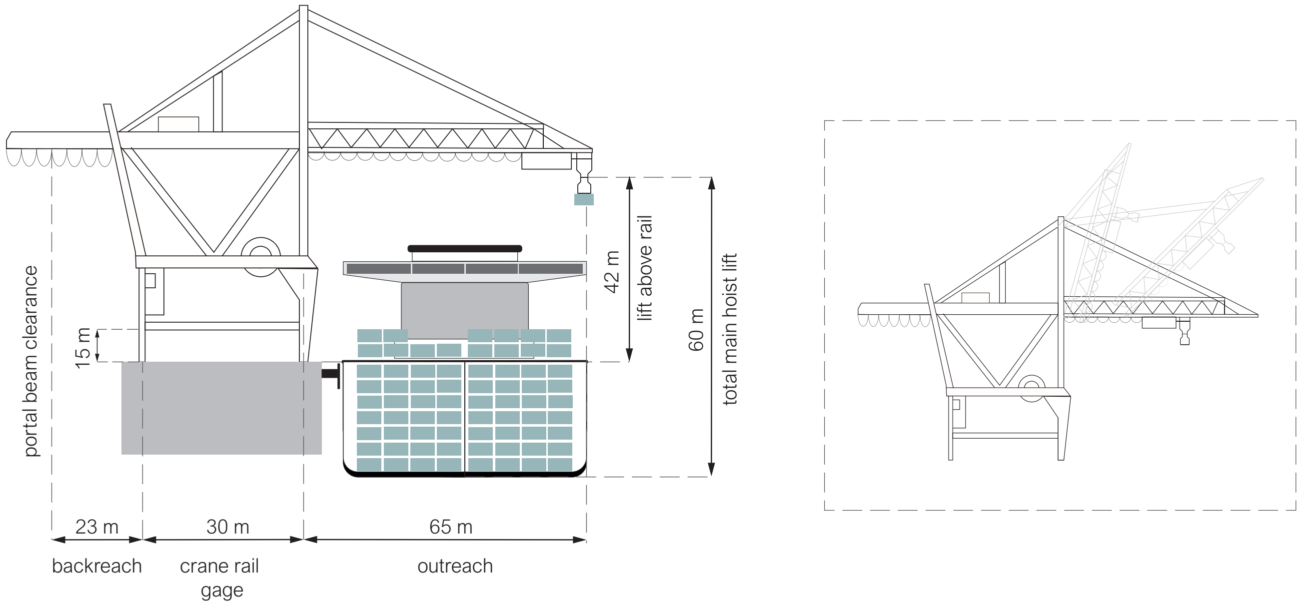


Figure 4.16: A-frame STS crane with typical dimensions for handling Super - Post Panamax vessels (modified from Bartosek and Marek, 2013, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

- *Width between legs* – min. 16 m, to allow oversized containers to pass.
- *Crane productivity* – peak 40-50 moves/hr, average 20-30 moves/hr.

Crane productivity is a key indicator and one of the critical parts of overall terminal productivity. The productivity of an STS crane is measured by the number of moves per hour. One move equals a move of a container between vessel and transport vehicle or vice versa. Feeder vessels are being served by 1-2 STS cranes, while Super - Post Panamax vessels can be served by 6-8 STS cranes (Figure 4.17). The STS cranes at the ECT Euromax terminal have a reach of 23 containers wide.

Figure 4.17: 21,000 TEU COSCO Development being handled by six STS cranes at Euromax terminal in the port of Rotterdam (SIF W & COSCO NEBULA by kees torn is licenced under CC BY-SA 2.0).

4.3.2 Between quay and storage yard

For the transport between quay and storage areas several options exist, depending on the size and the throughput of the terminal and the preferences of its operator. In increasing order of sophistication these are:

- *Toploaders (Figure 4.18, left)* – In the past Forklift Trucks (FLTs) were used, nowadays toploaders. Toploaders are equipped with a spreader to pick up a container from above and are capable of handling loaded containers. Top loaders need sideway access to a stack, which can therefore be only two containers wide. This requires much space between the stacks. On multipurpose terminals with limited container throughput and much space this type of equipment offers an economic solution. Empty container handlers are used in the empty container depot, their lifting capacity is smaller than that of top loaders. Empty container handlers pick up the containers sideways.
- *Reach Stacker (RS) (Figure 4.18, right)* – The difference from the FLT is that this device handles the container by means of a boom with a spreader. Hence it can reach the second row of containers in a stack, which can therefore be four rows wide. Yet, space efficiency is rather low. Another disadvantage is the relatively high front axle load (up to 100 tons), which asks for strong pavement.

Figure 4.18: Container handling equipment; left: toploader (by Gazouya-japan is licenced under CC BY-SA 4.0); right: reach stacker (by NAC is licenced under CC BY-SA 4.0).

- *Chassis (Figure 4.19, left)* – Single trailers for use in the yard only, where they are moved by tractor units. The containers are stored on the chassis. This approach, quite customary in U.S. ports, has the disadvantage of low space utilisation as compared with the stacking approach applied in Europe and Asia. It is very easy, however, to select containers and remove them from the stack.
- *Straddle Carrier (SC) (Figure 4.19, right)* – For this equipment the stack consists of (not too lengthy) rows of containers, separated by lanes wide enough for the legs and tyres of the SC. Depending on the nominal stack height, 2- or 3-high, the SC can lift a container 1 over 2 or 1 over 3. Certainly in the latter case the SC becomes quite tall and difficult to manoeuvre since the driver cabin is on top. However, for reasons of space efficiency and flexibility the SC is quite popular among terminal operators.

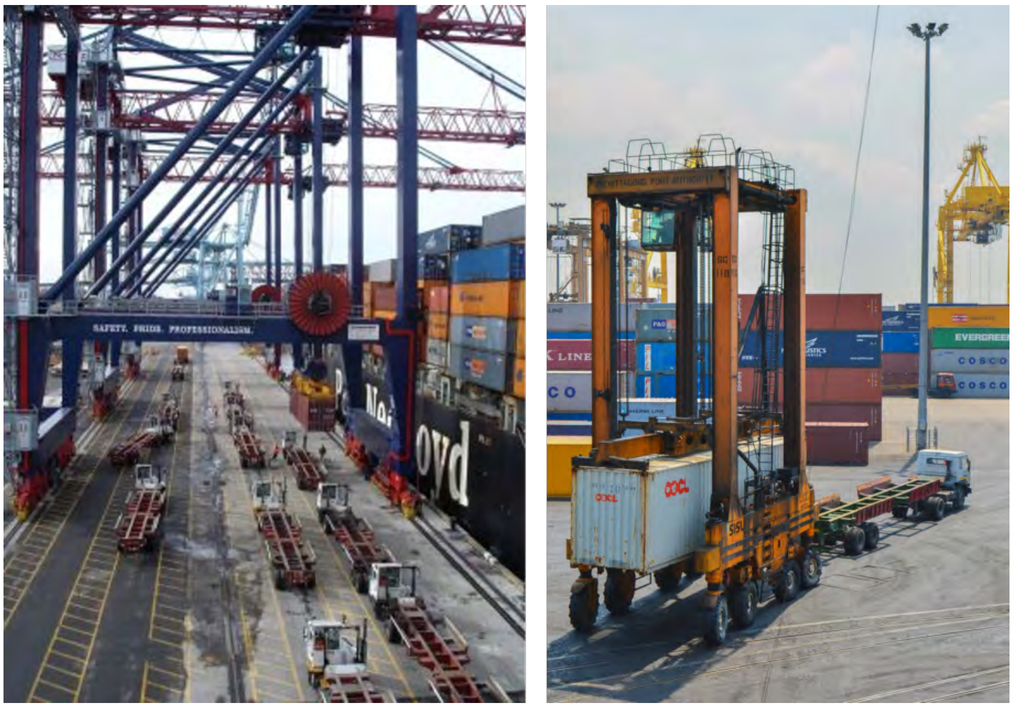


Figure 4.19: Container handling equipment; left: chassis (from www.portstrategy.com, "Take a load off", Copyright by Mercator Media Ltd 2021); right: straddle carrier (SC from Port of Chittagong by Moheen Reeyad is licenced under CC BY-SA 4.0).

The above four types of equipment deal with the transport from quay to storage yard and within the yard. In high capacity terminals the two functions are often separated, with dedicated cranes within the stack and the following types of vehicles for transport between quay and yard:

- *Multi Trailer System (MTS), Figure 4.20, left)* – A series of up to 5 interconnected trailers is pulled by one yard tractor. This offers a substantial reduction of the number of drivers needed. The system, developed and manufactured in The Netherlands, has a special device to keep all trailers in line when making a turn. MTS is not a very common means of horizontal transport on the larger and modern terminals nowadays. On the other hand MTS can be a very suitable on dedicated interconnecting lanes between terminals in a port complex.
- *Automated Guided Vehicle (AGV), Figure 4.20, right)* – Developed and first implemented by ECT on the Delta-SeaLand terminal on the Maasvlakte. They are fully automated and therefore mean a further drastic reduction of manpower.

Figure 4.20: Container transport vehicles; left: Multi Trailer System (MTS) (by Govender et al., 2017, is licenced under CC BY 4.0); right: Automated Guided Vehicle (AGV) (by Europe Container Terminals (ECT) is licenced under CC BY-NC-SA 4.0).

- *Lift AGVs (Figure 4.21* – are a further development of AGV technology. Unlike conventional AGVs, the lift AGV has two active lifting platforms. These enable the vehicle to lift and place containers independently on transfer racks in the interchange zone in front of the stacking cranes. Two 20' containers can be handled independently, as well as one other container of any size. This can result in shorter downtimes and increased working frequency.

Figure 4.21: Lift Automated Guided Vehicle (Lift-AGV) (from www.konecranes.com, "Lift AGV", Copyright by 2021 Konecranes).

Advantages	Disadvantages
Top Loader (TL) / Reach Stacker (RS)	
low investment equipment	much storage capacity needed
simple / flexible in operation	labour intensive
Straddle Carrier (SC)	
high throughput capacity	complicated equipment
one type of equipment for entire terminal	high investment and maintenance costs
	highly qualified personnel needed
	labour intensive
Automated Guided Vehicle (AGV)	
minimal labour costs	high investment and maintenance costs
high throughput capacity	complicated and sensitive equipment

Table 4.3: Quay-to-storage transport and container handling systems (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

4.3.3 Within the storage yard

The MTS and AGVs deliver the containers outside the stacks and for further handling within the stack separate equipment is needed. Various types of gantry cranes are used as described below:

- *Rubber Tyred Gantry (RTG), Figure 4.22* – This type is commonly used in stacks up to about 6 containers wide and about 5 high. They are flexible (can be moved from one stack to another), but require good subsoil conditions or a track with adequate foundation, in view of the relatively high wheel loads;

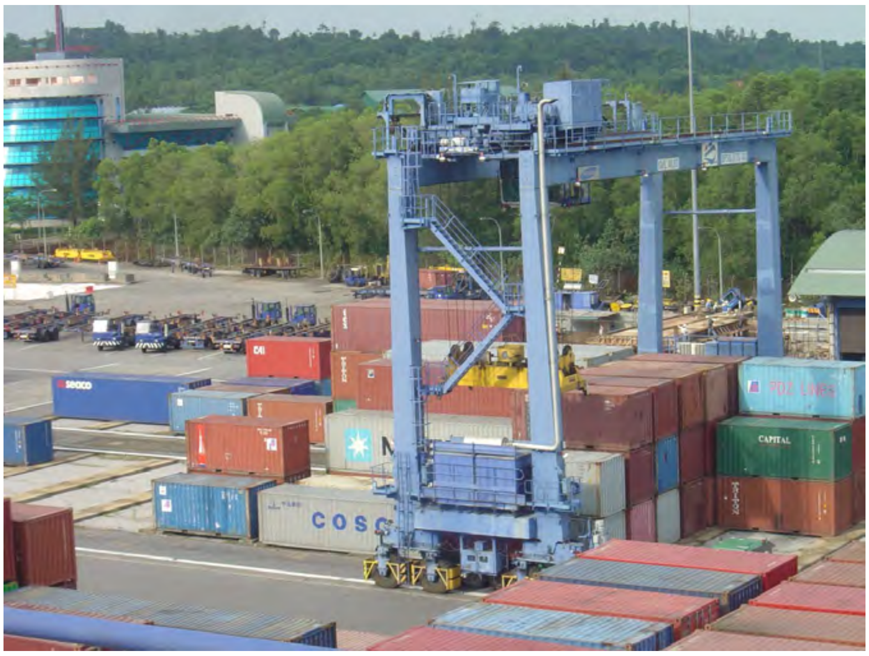


Figure 4.22: Rubber Tired Gantry crane (RTG) (RTG at Bintulu International Container Terminal (BICT) by R.W. Sinyem is licenced under CC BY 2.0).

- *Rail Mounted Gantry (RMG), Figure 4.23* – Where the subsoil conditions are less favourable or loads are heavier the RMG is preferable, because the rails spread the load better. Notwithstanding the greater span of the crane (up to 10 containers wide) the crane bogies provide for lesser wheel loads. Also, the rail can be more easily supported, if needed.

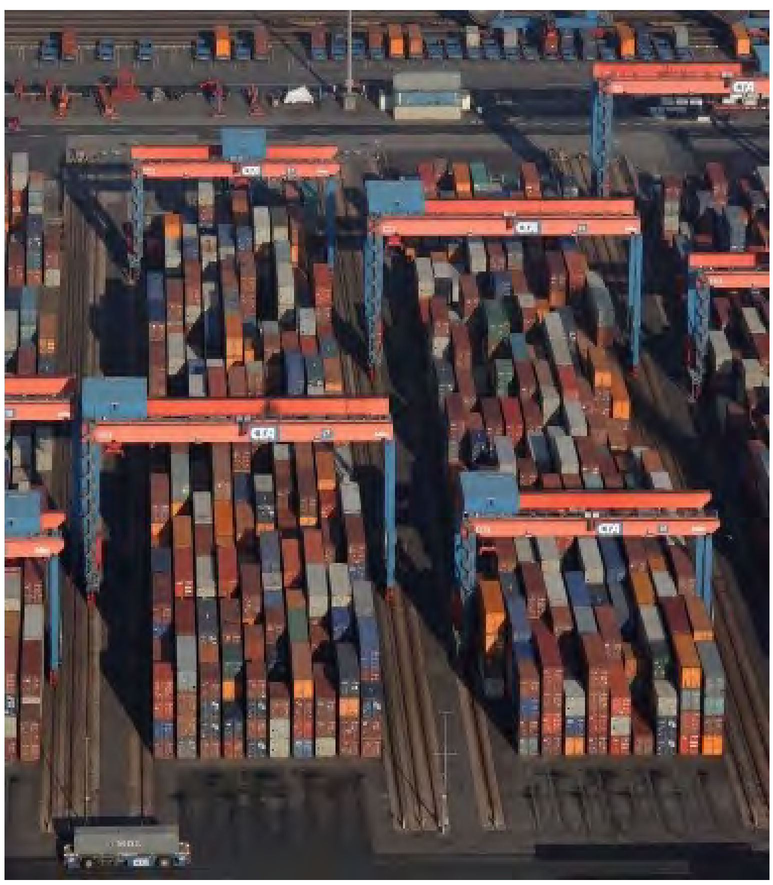


Figure 4.23: Rail mounted gantry cranes (RMGs) at the Altenwerder terminal, Hamburg (Port of Hamburg, Container Terminal Altenwerder by Dirtsc is licenced under CC BY-SA 3.0).

- While most RMGs have the rails at ground level, a terminal in Singapore has an overhead crane running on rails at 18 m above ground level, mounted on beams supported by concrete columns; this type is referred to as Overhead Bridge Crane (OBC);
- *Automated Stacking Crane (ASC), Figure 4.24* – The first cranes of this type were introduced by ECT in conjunction with the AGVs. They reach across about 10 containers and operate 1 over 4 high at most terminals (for instance ECT Euromax terminal at Maasvlakte, Rotterdam).

Figure 4.24: Automated Stacking Cranes (ASCs) (by ECT is licensed under CC BY-NC-SA 4.0).

Advantages	Disadvantages
Rubber Tyred Gantry (RTG)	
good space utilisation	high maintenance costs
flexible, high occupancy rate	labour intensive
reasonable productivity	
Rail Mounted Gantry (RMG)	
good space utilisation	high investment costs
reliable, low maintenance costs	inflexible
automation and relatively high productivity possible	
Automated Stacking Crane (ASC)	
minimal labour costs	higher investment than for RMG
high capacity	

Table 4.4: Equipment within the stacks (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

4.3.4 From storage to hinterland transport

The transport of containers between the stacks and the truck stations (and vice versa) is done mostly by the equipment that is also used in the stack. At a terminal with straddle carriers, for instance, these bring the containers to the truck station and position them on the trucks (see Figure 4.19, right). Depending on the distance, various types of equipment are used for transport from the yard to a rail or inland barge terminal. The same considerations apply as for the equipment between quay and storage yard (see above).

There are basically three modes of container transport to the hinterland:

- *Road transport* – via the truck station and the gate,
- *Rail transport* – via a rail terminal,
- *IWT transport* – via the IWT terminal.

The gate

For road transport the gate is a central element on the terminal (Figure 4.25). Here imported containers leave the terminal and containers to be exported arrive. All entries and departures are recorded and customs formalities are dealt with here. High-capacity terminals require advanced information technology to avoid frequent queues and long waiting times for the trucks.

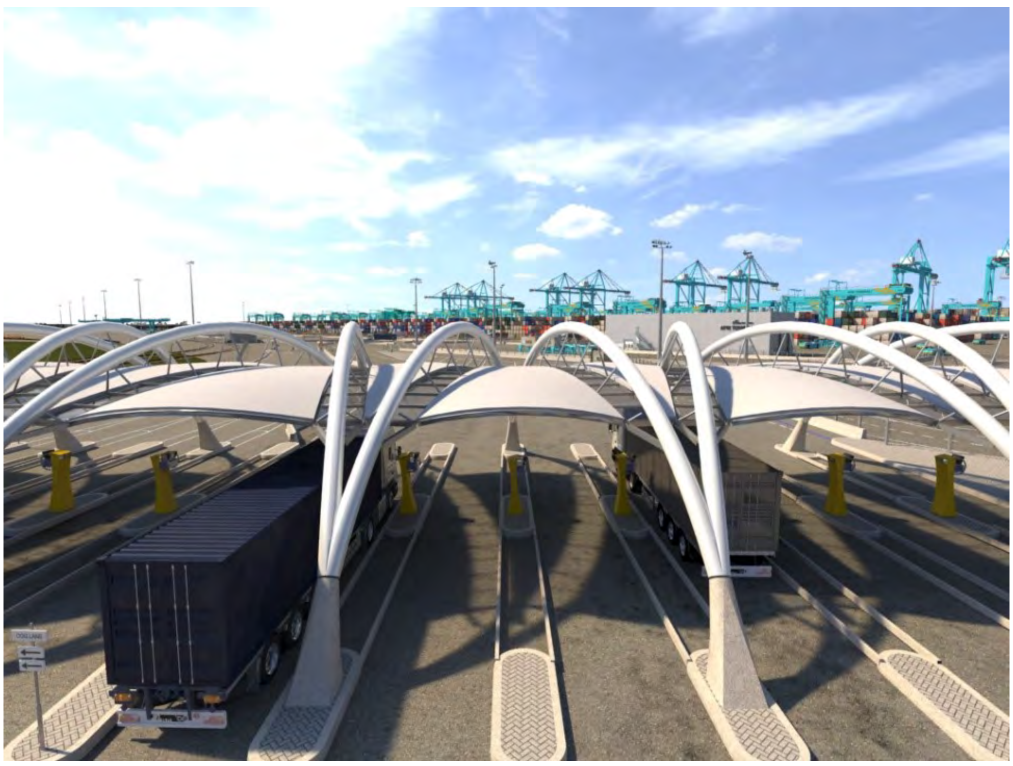


Figure 4.25: The gate (canopy) at APMT Maasvlakte 2 terminal, artist impression (Verkeersportaal APM Terminals by APM Terminals is licenced under CC BY-NC-SA 4.0).

As described in PIANC (2014b), the gate facilities are usually divided into an entrance or receiving gate for trucks entering and a separate exit gate for trucks exiting the terminal. The number of entrance and exit lanes required is determined by the predicted level of traffic for the terminal.

Many modern terminals using Automatic Equipment Identification System (AEIS) (standardised by ISO/TC 104/SC 04/WG 02 "AEI for containers and container related equipment") have a pre-gate entrance system. This divides the gate procedure into two parts, thus reducing the required time at the gate itself and, consequently, the number of lanes and space required:

- At Position 1 (pre-check) the necessary information, such as booking numbers, is exchanged between a clerk in the control room and the truck driver. An AEIS reader puts the container's code into the terminal's computer system.
- Subsequently, the truck is driven to the gatehouse (Position 2) where remaining gate procedures are carried out.

As described in PIANC (2014b), the terminal gate often has to provide space to accommodate additional port functions such as:

- *Port Security and ISPS compliance* – The requirement is to verify the identity of anyone passing the demarcation (usually a fence) between the port and terminal area proper.

- *Radiation Detection* – to incoming and outgoing containers. This check is accomplished by special mobile or fixed equipment called Radiation Portal Monitors.
- *Customs inspections* – Usually an area near the exit gate has to be set aside for the customs officials to be able to selectively inspect the content of incoming containers for contraband and collect the customs duty. At many terminals in the developing world the customs inspection procedure is time consuming, which often constitutes a bottleneck in the flow of containers. In such cases separate facilities ought to be provided. The application of X-ray equipment for customs control is quite common nowadays, also more and more in developing countries.
- *Reefer and agricultural inspections* – This requires an area for trucks to be set aside, similar to the Customs inspection above.
- *Port health inspections* – Ports are locations from where infectious diseases, such as SARS and Covid-19, may spread; a port coming under the World Health Organisation (WHO) International Health Regulations is held to infectious disease control.
- *Weighbridge* – One or more of these may be required for a variety of reasons, such as verifying cargo weights, or checking for vehicle wheel pressures exceeding the highway limit.
- *Damage inspections* – It is normal to have cameras incorporated in the gate complex for the general external inspection of containers for insurance purposes.

Rail terminal

Transfer to and from rail can be done on or outside the container terminal. For logistic reasons, the railroad track inside a terminal often runs parallel to the truck transfer area. Figure 4.26 shows an example of such a rail terminal.

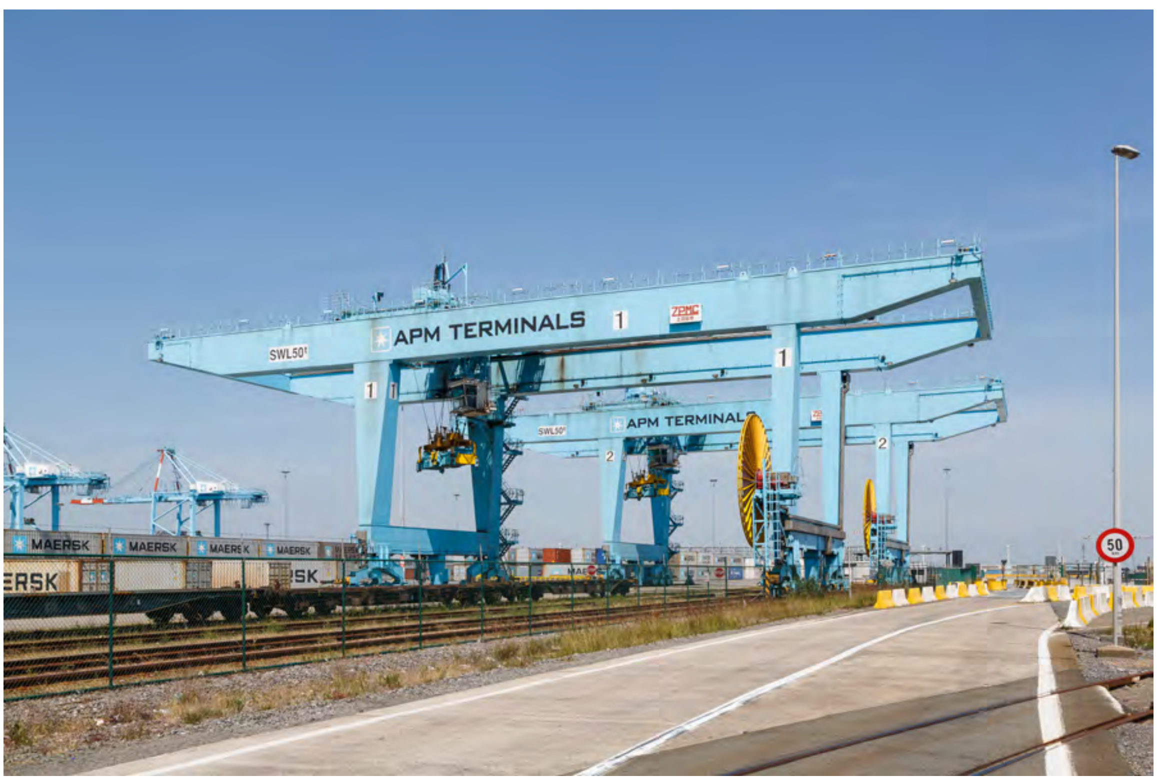


Figure 4.26: APMT Zeebrugge (Belgium) rail terminal with gantry crane (by CEphoto, Uwe Aranas is licenced under CC-BY-SA 3.0).

Not all rail yards are inside a terminal (on-dock). Off-dock ones (also called Rail Service Centre (RSC)) generally serve more than one terminal. Transfer from container terminal to RSC and vice versa is done by trailers which have to pass the gate. On other terminals an internal road may connect to the RSC, thus allowing the use of terminal equipment, such as MTS.

IWT terminal

Depending on the terminal (busy or not busy, large or small vessels) the transfer of containers to and from IWT barges is done along the quays for sea-going vessels, or at separate quays. Handling IWT-barges at quays for sea-going vessels has a number of distinct disadvantages:

- The STS cranes are too large for handling the small barges, whence crane productivity is relatively low.
- When a sea-going vessel arrives, it usually gets priority and handling of the barge is interrupted.
- The barges often collect their cargo at several terminals, which may be time consuming, especially if they have to give priority to sea-going vessels.

A separate barge terminal with suitable equipment and linked to the main one is a way to overcome the former disadvantages. Figure 4.27 shows such a barge terminal, at ECT's Delta Terminal on the Maasvlakte. Note that this one is combined with a rail and a road terminal.

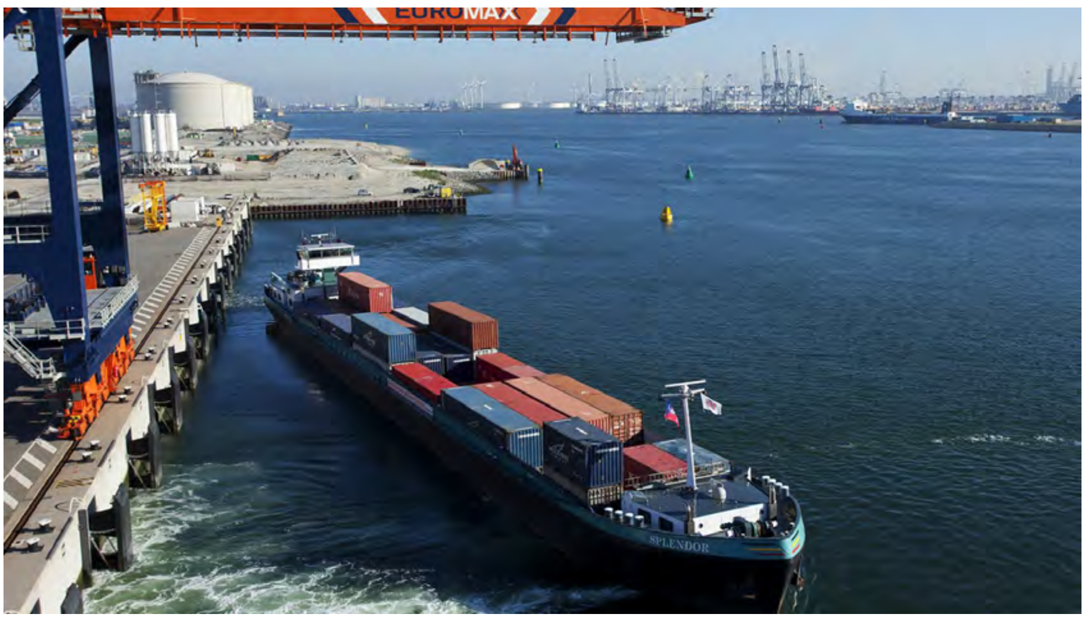


Figure 4.27: IWT-vessel leaving ECT Euromax terminal, Maasvlakte, Rotterdam (image by Eric Bakker and Port of Rotterdam is licenced under CC BY 4.0).

In order to overcome all three disadvantages one might consider building a general barge terminal with connections to the different container terminals. However, this introduces an additional step in the transport process with two times extra handling. The associated extra cost makes this solution unattractive. Yet, the rapid increase of container transport by barge is likely to render a multi-user concept attractive. Such Barge Service Centres (BSCs) could be similar to RSCs, with internal connections to the surrounding container terminals. Such a concept requires co-operation of all users (container terminal operators).

Other buildings

Other buildings encountered on the terminal include the office building and the workshop for repair and maintenance of the equipment. The requirements vary per terminal.

4.4 Estimation of terminal elements and layout

Figure 4.28 gives a typical container terminal layout and Figure 4.29 summarises the most important components. A terminal layout depends to a large extent on the selected yard handling systems. Other determining factors are related to the context in which the terminal is to be realised.

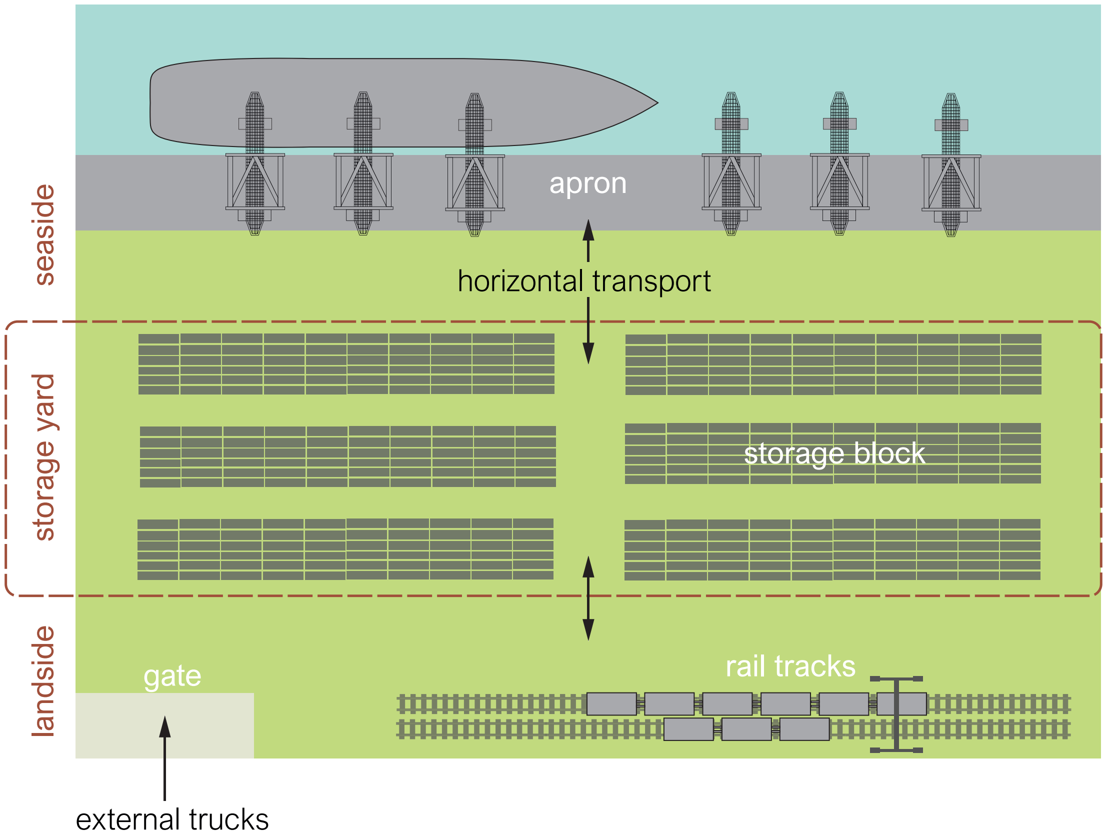


Figure 4.28: Typical container terminal layout (modified from Böse, 2011, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

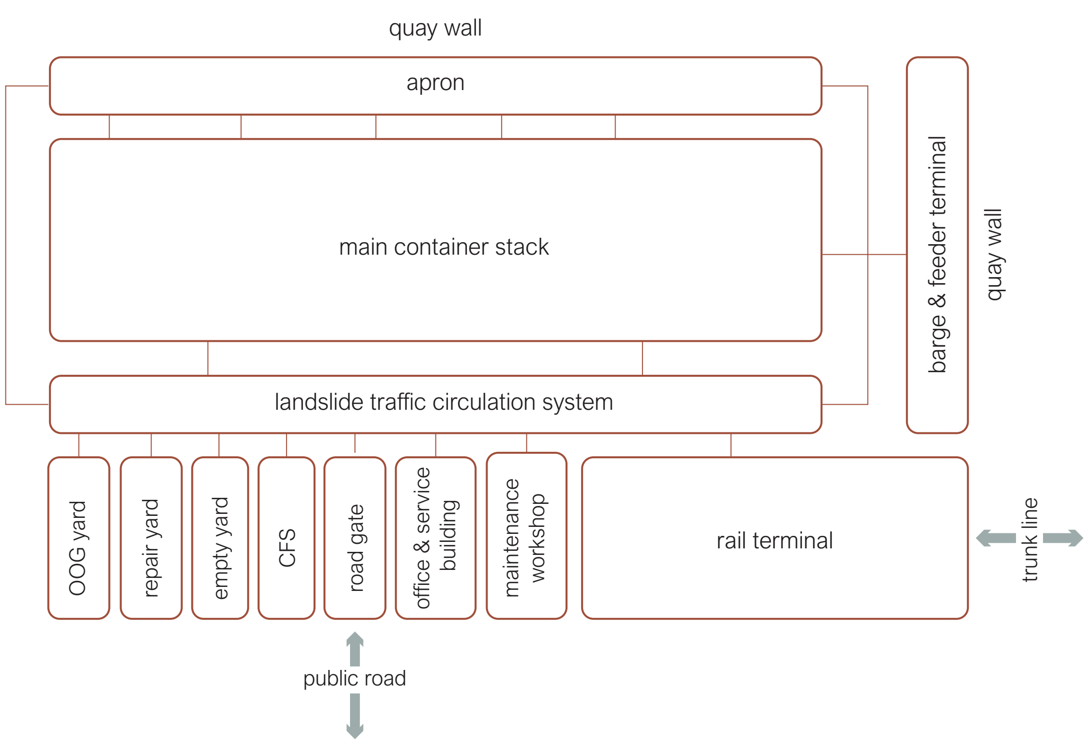


Figure 4.29: Terminal components (modified from PIANC, 2014b, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The planning of a new terminal often starts from the operator's preference for a specific stacking system in combination with a specific horizontal transport system. For a first-order functional design and feasibility analysis the following terminal components have to be specified:

- *Seaside* – number of STS cranes, quay length, quay retaining height and apron area,
- *Storage yard* – storage area and yard equipment,
- *Landside* – container transfer area (to truck, rail and IWT), and
- *Other* – supporting buildings such as offices, workshops, a Container Freight Station (CFS), et cetera.

In the following sections we will consider these items one by one and see how they interact with the others in a coherent layout. We will illustrate this by an example, which we will elaborate step by step, following the steps outlined in Section 3.3.3.

4.4.1 Step 1: Cargo forecast

Before we can determine numbers and dimensions of terminal elements, we need to know more about the cargo flows and the vessels to be expected. Table 4.5 shows the values that are used for our example.

Cargo estimates	
Annual cargo throughput	2,460,000 TEU
Percentage import	15%
Percentage export	16%
Percentage transhipment	69%
Peak factor	1.2
TEU-factor	1.6

Table 4.5: Cargo forecast (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

So this is a terminal with a relatively large percentage of transshipment. In order to increase the service level and limit maximum waiting times, the port authority has chosen a peak factor 1.2. The TEU-factor indicates the average container size as compared with the standard twenty-foot container.

4.4.2 Step 2: Fleet composition, cargo distribution

In order to know how often what type of vessels will call how many times per year at the terminal, we need to forecast the vessel mix and the call size. We assume three vessel classes will call on this terminal in a 40-30-30 percent split (see Table 4.6).

Vessel class	Vessel mix	Cargo flow	Call size	Nr. calls
Post Panamax I	40%	984,000 TEU	1,750 TEU	563
VLCS	30%	738,000 TEU	3,250 TEU	228
ULCS	30%	738,000 TEU	4,875 TEU	152
Total	**100%**	**2,460,000 TEU**	–	**943**

Table 4.6: Vessel mix and estimated number of calls per year (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Note that the total cargo throughput obtained by multiplying the number of calls of a vessel type by the call size does not add up to 2,460,000 TEU, but slightly more than that. This is because the number of calls has to be a round number. We use the original throughput C rather than one derived from the number of trips in the further calculations.

4.4.3 Step 3: Cargo specification

Transhipment cargo is handled twice at the quay (once when coming in and once when going out), but it is stored only once. Therefore, we have to distinguish between the throughput over the quay and over the terminal. We use the input values from Table 4.5 to make this distinction. This results in the split presented in Table 4.7.

Annual cargo flow	Quay	Loading	Unloading	Terminal
Import (sea – land)	369,000 TEU	–	369,000 TEU	369,000 TEU
Export (land – sea)	393,600 TEU	393,600 TEU	–	393,600 TEU
Transhipment (sea – sea)	1,697,400 TEU	848,700 TEU	848,700 TEU	848,700 TEU
Total	**2,460,000 TEU**	**1,242,300 TEU**	**1,217,700 TEU**	**1,611,300 TEU**

Table 4.7: Annual cargo flow (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Both for the capacity of the quay operations and for the configuration of the storage area we need a further specification of the cargo by type (ladens, reefers, empties, OOGs) and a translation of the quay and terminal throughputs from TEU to boxes to be handled. Table 4.8 shows the split percentages and TEU-factors we assume, and how this translates to throughput quantities in terms of TEU and boxes.

	Laden	Reefer	Empty	OOG
Percentage	70%	10%	19%	1%
TEU-factor	1.6	1.7	1.55	1.55
Quay throughput (TEU)	1,722,000 TEU	246,000 TEU	467,400 TEU	24,600 TEU
Quay throughput (boxes)	1,076,250 boxes	144,706 boxes	301,549 boxes	15,871 boxes
Terminal throughput (TEU)	1,127,910 TEU	161,130 TEU	306,147 TEU	16,113 TEU
Terminal throughput (boxes)	704,944 boxes	94,782 boxes	197,514 boxes	10,395 boxes

Table 4.8: Cargo type specification (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The annual quay throughput in boxes is obtained by dividing the annual throughput in TEU (adding up to 2,460,000 TEU) by the TEU-factor. This leads to a total number of 1,538,375 boxes that need to be handled at the quay annually.

Similarly, the terminal or stack throughput is found by dividing the annual terminal throughput in TEU (adding up to 1,611,300 TEU) by the TEU-factor. This gives a total number of 1,007,635 boxes to be handled at the terminal annually.

4.4.4 Step 4: Berth configuration

Vessel properties The dimensions of a single berth depend on the size of the vessels to be accommodated. The times needed for mooring and unmooring may also depend on the vessel type (here selected to be equal).

Vessel class	Length (L_{OA})	Draught (D_s)	Beam (B_s)	Mooring	Unmooring
Post Panamax I	300 m	13 m	40 m	1 hr	1 hr
VLCS	397 m	15.5 m	56 m	1 hr	1 hr
ULCS	400 m	16 m	59 m	1 hr	1 hr

Table 4.9: Vessel properties (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Cargo handling equipment In order the determine the berth and quay configuration, we need information on the cargo handling equipment at the quay. Here we assume the loading/unloading to be done with STS-cranes and the transport to and from the storage yard by tractor trailers. Empties are handled by special equipment.

Quantity	Number	Units
Operational hours	8592	hours/year
Hourly cycles per STS crane	30	lifts/hour
Lifting capacity	2	TEU/lift
Max. nr. of crane slots per berth	4	crane slots/berth
Tractor trailers	5	tractor trailers/crane
Empty handlers	40,000	moves per handler/year

Table 4.10: Cargo handling equipment (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The number of lifts per hour and the capacity per lift determine the crane productivity, though a widely accepted productivity definition is lacking. Here we use the average number of lifts per hour between the moment that berthing is completed and the moment that de-berthing starts. This period includes all sorts of 'unproductive' time intervals, such as the time needed for crane repositioning from one bay to another, for removal of hatches and placing them back, for changing shifts and for simple repairs to the cranes. A potential peak production of 40-50 lifts per hour is easily reduced to a net value of 30 lifts per hour due to these losses.

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

With the information we now have available we can work out how many berths / quay sections and pieces of unloading and transporting equipment we need to handle the cargo throughput (see also Section 3.3.3). The determining factor is the waiting time to service time (WT/ST) ratio. We select 0.1 as a maximum acceptable value of this ratio which is common for container terminals (see also PIANC, 2014b). In the present example we use the E2/E2/n table from queueing theory to determine the required number of berths and the corresponding berth occupancy (see Table 3.10).

We start from a greenfield situation and increase the number of berths step by step until we have achieved the required WT/ST ratio. The total (un)loading time is determined by multiplying the total TEU over the quay with the peak factor and dividing by the hourly lifting capacity in TEU of the crane(s). The total (un)mooring time is 1886 hours in this example (Nr. calls × 2 hours). The berth occupancy factor follows from:

$$\text{occupancy} = (\text{Total (un)loading time} + \text{Total (un)mooring time})/\text{operational hours} \tag{4.2}$$

For this example 4 berths and 14 STS cranes are sufficient to achieve an acceptable service level.

In practice the number of STS cranes per berth depends on several additional factors, such as:

- the range of vessel sizes and the (weighted) average size,
- the number of berths,
- the stowage plan, and
- the maximum number of cranes that can operate on one vessel.

Along a conventional linear quay cranes can work on any berth. For practical reasons (including the transport between the STS cranes and the storage yard) Post Panamax vessels have not more than 5 cranes working simultaneously. Smaller vessels have fewer cranes. If a new terminal would start with just one berth and had to handle Post Panamax vessels efficiently, 5 cranes would be needed for that single berth. For the latest generation of vessels this is not even enough (see, for instance, Figure 4.17). If, on the other hand, a quay consists of several berths and the berth occupancy is low, it is possible to reduce the average number of cranes per berth.

Step 4.2: Quay length

Now that we know how many berths are needed, we can work out the total quay length. We assume a linear arrangement, with all berths in line, and with a berthing gap of 15 m for all vessels and at either end of the quay structure (PIANC, 2014b, p. 98, suggests 15 – 30 m; Table 3.2 gives numbers differentiated by vessel type). One

Iteration	Action	Configuration		(Un)loading	Occupancy	WS/ST
		Berths	Cranes			
0	greenfield	–	–	–	–	–
1	add berth	1	–	–	–	–
2	add crane	1	1	49200.0	5.95	> 4.3590
3	add crane	1	2	24600.0	3.08	> 4.3590
4	add crane	1	3	16400.0	2.13	> 4.3590
5	add crane	1	4	12300.0	1.65	> 4.3590
6	add berth	2	–	–	–	–
7	add crane	2	5	9840.0	1.36	> 2.0000
8	add crane	2	6	8200.0	1.17	> 2.0000
9	add crane	2	7	7028.6	1.04	> 2.0000
10	add crane	2	8	6150.0	0.94	> 2.0000
11	add berth	3	–	–	–	–
12	add crane	3	9	5466.7	0.86	0.8726
13	add crane	3	10	4920.0	0.79	0.4417
14	add crane	3	11	4472.7	0.74	0.3207
15	add crane	3	12	4100.0	0.70	0.2236
16	add berth	4	–	–	–	–
17	add crane	4	13	3784.6	0.66	0.1120
18	**add crane**	**4**	**14**	**3514.3**	**0.63**	**0.0868**

Table 4.11: Number of berths, quays and cranes (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

may choose to dimension one berth for the largest vessel calling at the terminal; all other berths are designed on the basis of the average vessel length. This leads to the following formula for the total quay length (see also Section 3.3):

$$L_q = 15 + L_{s,max} + 1.1(n-1)(15 + L_{s,av}) + 15 \tag{4.3}$$

in which n is the total number of berths.

The factor 1.1 follows from a study carried out by (UNCTAD, 1985). They determined, for a number of actually observed vessel length distributions and berth lengths, the probability of occurrence of additional waiting time due to simultaneous berthing of above-average vessels (Figure 4.30).

The correction of the total port time in this figure accounts for additional waiting time. The diagram shows that with an average berth length of 10% above the average sum of ship length plus berthing gap no additional waiting time occurs.

As the number of berths in a row increases, the correction factor will theoretically tend to 1.0. In practice this is not the case, because vessels will seldom be shifted during operations, in view of the additional delays this causes. For more complex arrangements see Section 3.1.3. For our current example we arrive at a total quay length required of 1600.1 m (see Table 4.12).

Quay length calculations	
Largest vessel length ($L_{s,max}$)	400 m
Average vessel length ($L_{s,av}$)	339.57 m
Number of berths (n)	4
Total quay length	**15 + 400 + 1.1 * (4 -1) * (15 + 339.57) + 15 = 1600.1 m**

Table 4.12: Quay length calculation (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

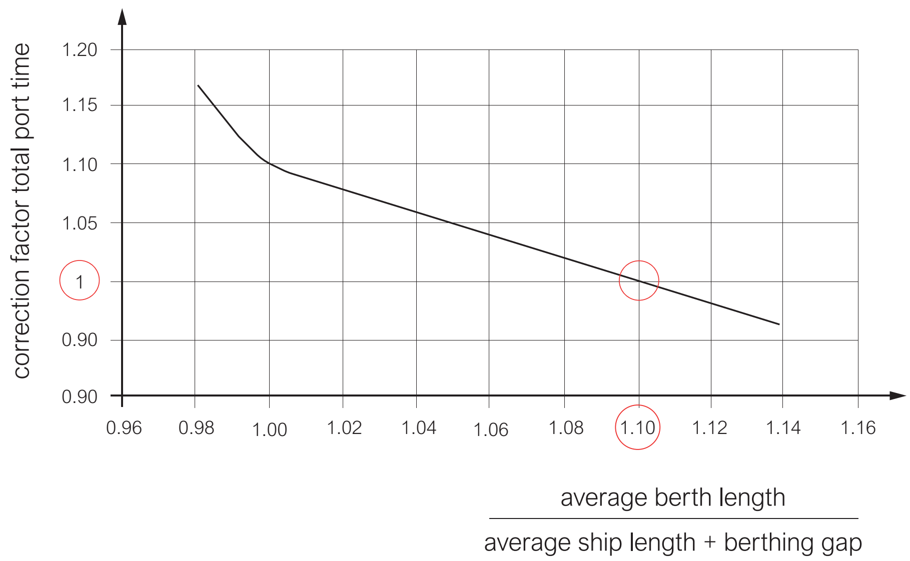


Figure 4.30: Correction factor for the total port time (reworked from UNCTAD, 1985, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Step 4.3: Quaywall retaining height

The vertical distance from the quay platform to the bottom level of the berth is a relevant design parameter for the quay structure, such as an earth retaining quay wall. Starting from the bottom it consist of bed level parameters, the Under Keel Clearance (UKC) of the vessel, its draught, allowances for vertical motions (including sinkage and wave-induced vertical motion) and a freeboard (see Table 4.13).

Retaining height	
Disturbed soil	0.5 m
Dredging tolerance	0.5 m
Maintenance allowance	0.5 m
UKC	0.5 m
Max draught	16.0 m
Max sinkage	0.5 m
Wave motion	0.5 m
Freeboard	4.0 m
Total quay retaining height	**6 * 0.5 + 16.0 + 4.0 = 23.0 m**

Table 4.13: Quay wall retaining height (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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

Step 4.4: Apron surface area

Once the quay length has been determined, one can address the layout of the apron area. Moving from the waterfront inwards one encounters (Figure 4.31):

1. a setback of 3 – 5 m between the coping and the waterside crane rail, to provide access to the vessels for crew, supplies and services. This space is also necessary to prevent damage to the crane by the flared bow of the vessel during berthing under some angle. In the setback area are bollards and shore power connection pits.

2. the crane track spacing, which is primarily determined by considerations of crane stability. A second aspect is the space required for the transport equipment and Automatic Twistlock (ATL) removal/application. On most terminals the containers are dropped off or picked up by the STS crane within the space between the crane rails. When four STS cranes are working on one vessel, each has transport equipment lining up, preferably on separate lanes for safety reasons. Depending on the number of crossings of the landward rail over the length of the quay, there may be need for additional lanes. The space between the rails of cranes should accommodate a number of truck lanes depending on how many cranes are on the quay. The three lanes are 16 m for smaller terminals (two lanes for trucks waiting containers, one for overtaking) or four lanes are 20 m. Large Post Panamax cranes now have 30.48 m – 35 m rail spacing. In the end there is also a feedback between crane designer, marine civil engineer and operational planning of number of lanes.
3. the space immediately landward of the landside rail, which is used to place the hatch covers and/or to lift special containers, such as flats with bulky or hazardous cargo.
4. a traffic lane for the SCs, the Tractor-Trailers (TTs), MTSs or AGVs which commute between the storage yard and the quay. The width depends on the transport system adopted. For SCs 2 lanes are usually sufficient, whereas for AGVs a width equal to that between the crane rails is required.

Note that no hinterland connections are allowed on the apron, contrary to the conventional general cargo terminals, where truck- and rail access to the quay was customary. For reasons of efficiency and safety this is not common on modern container terminals.

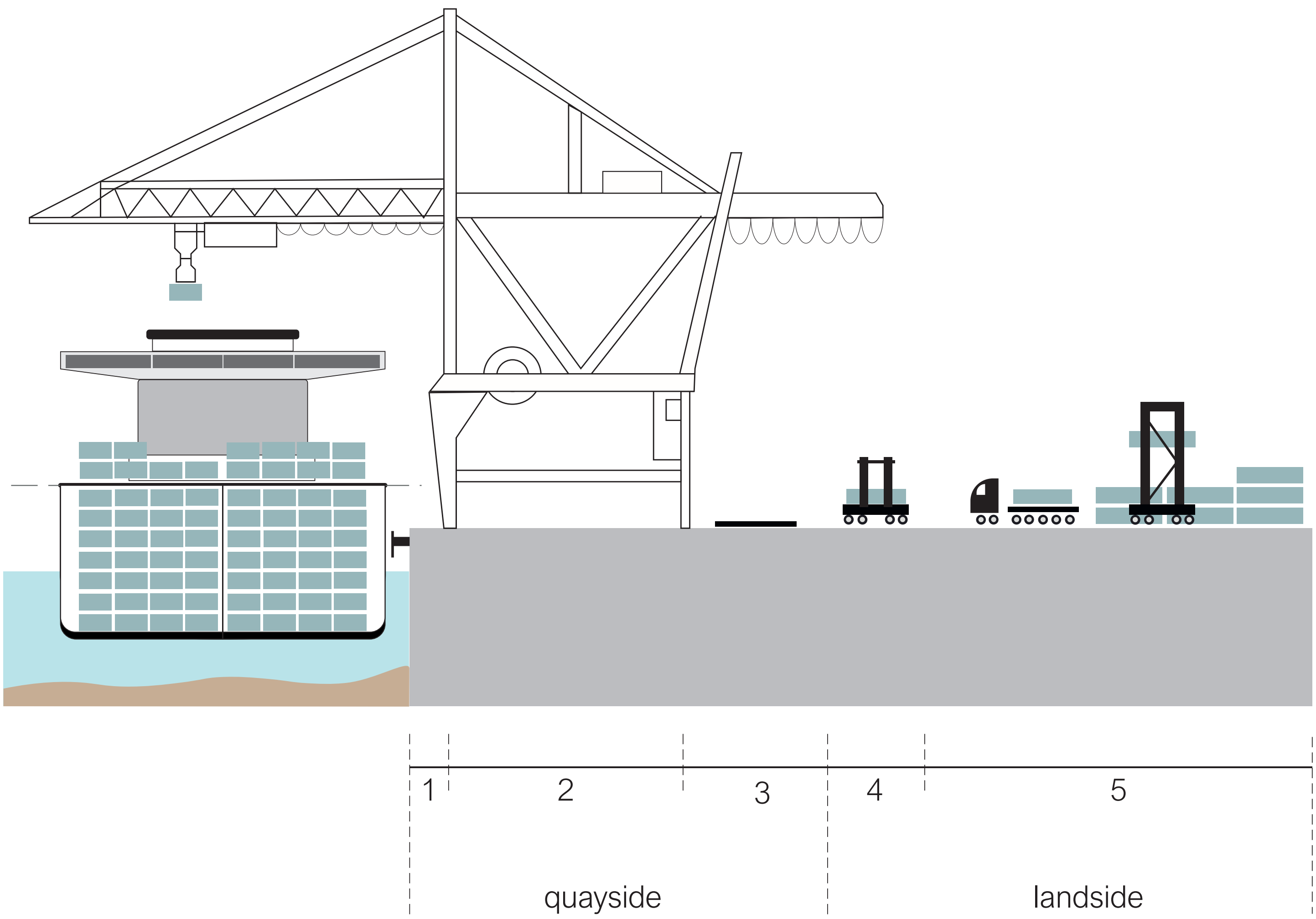


Figure 4.31: Apron lanes (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

In this example we assume a total apron width of 82 m (setback waterside rail track: 5 m, spacing crane tracks: 35 m, hatch covers / OOGs: 26 m, traffic lane: 16 m). Multiplying the apron width with the apron length (assumed here to be equal to the quay length) yields the apron area (see Table 4.14).

Apron surface area	
Total apron width	82 m
Apron length (= quay length)	1600.1 m
Total apron area	**82 * 1600.1 = 131,207 m^2**

Table 4.14: Apron surface area (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

4.4.5 Step 5: Quay to storage transport equipment

Next, we need to specify the transport equipment between quay and storage and the container handling equipment at the storage yard. In order to prevent congestion, the amount of transport equipment has to correspond with the crane capacity at the quay. Proportionality with the number of cranes therefore makes sense (see also Table 4.10). Table 4.15 shows the number of tractor trailers that is needed in this example.

Number of tractor trailers	
Nr of STS cranes	14
Trailers per STS crane	5
Total nr of tractor trailers	**14 * 5 = 70**

Table 4.15: Number of tractor trailers (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

At the storage yard, the first important choice is the stacking direction, as this influences the need for transport equipment. On the other hand, the type of transport equipment determines the space between the stacks and the maximum width and height of the stack (see also Part IV – Section 3.1).

4.4.6 Step 6: Storage area

An important factor when determining the area required for storage is the dwell time.

The average dwell time, $t_{d,av}$, has to be considered separately for import/export containers and empties. Dwell times for the latter are usually much longer. Also, fluctuations in dwell times may have to be considered, although $t_{d,av}$ is averaged over a large number of containers, so it will not vary much.

By definition, the average dwell time can be written as:

$$t_{d,av} = \frac{1}{S(0)} \int_0^\infty S(t)dt \tag{4.4}$$

in which $S(t)$ is the number of containers of a call at time $t = 0$ which is still on terminal.

ECT found that for their home-terminal the following dwell time function applies (see Figure 4.32):

$$\frac{S(t)}{S(0)} = \begin{cases} 1 & \text{for } 0 < t \leq 1 \\ \left(\frac{t_{d,max}-t}{t_{d,max}-1}\right)^2 & \text{for } 1 < t \leq t_{d,max} \\ 0 & \text{for } t > t_{d,max} \end{cases} \tag{4.5}$$

in which $t_{d,max}$ is the time at which 98% of the containers of the call have left the terminal again.

Substitution into Equation 4.4 yields:

$$t_{d,av} = (t_{d,max} + 2)/3 \tag{4.6}$$

A typical value of $t_{d,max}$ for terminals with a high turnover is 10 days, whereas in case of a low turnover it may amount to 30 days.

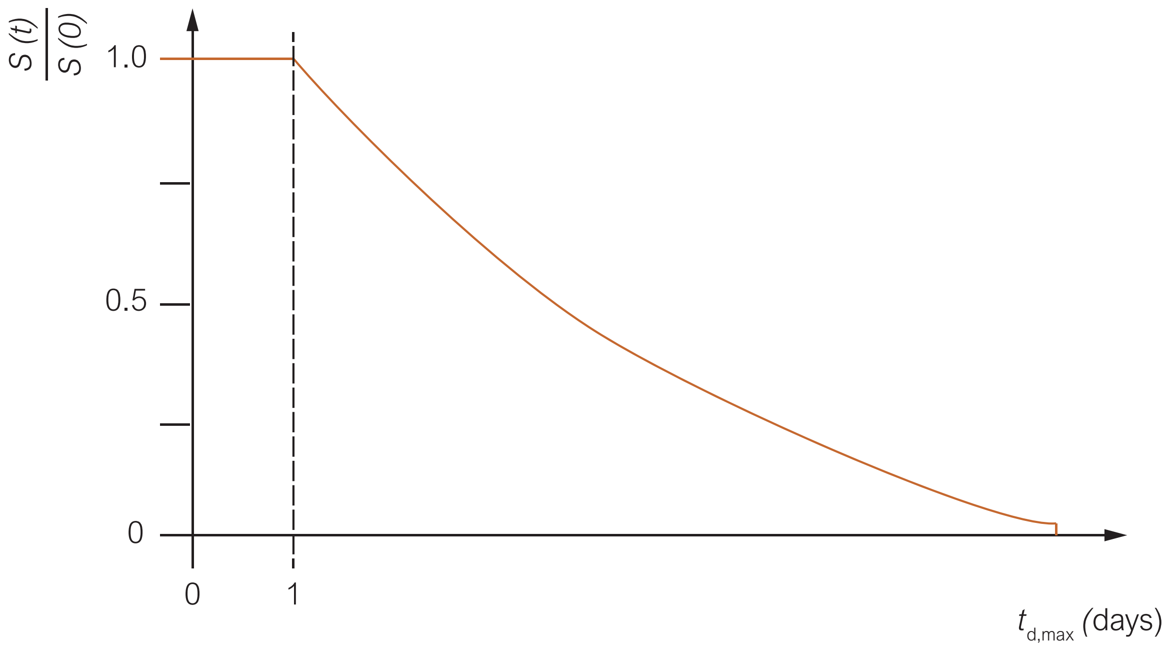


Figure 4.32: Typical dwell time function (at ECT) (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

For each container category (index k) we can now evaluate the number of TEU to be stacked from:

$$N_{s,k} = (C_k \cdot f_p \cdot t_{d,av})/d_{yr} \tag{4.7}$$

in which:
- $N_{s,k}$ = number of TEU of category k to be stacked [TEU],
- C_k = throughput of category k over the storage area [TEU/yr],
- f_p = peak factor [-],
- d_{yr} = number of operational days per year [days/yr].

Then the number of ground slots for containers of this category amounts to

$$N_{tgs} = N_{s,k}/(r_{st} \cdot m_c \cdot H_{n,st}) \tag{4.8}$$

in which:
- N_{tgs} = number of ground slots required for this category of containers,
- r_{st} = ratio of average stacking height over the nominal stacking height (usually 0.6 to 0.9),
- m_c = occupation rate (usually 0.65 to 0.70),
- $H_{n,st}$ = nominal stacking height.

The factor r_{st} in Equation 4.8 reflects the fact that the sequence in which the containers will leave the stack is partly unknown (mostly so for the import stack) and that extensive intermediate re-positioning of containers is expensive. Statistically, the need for re-positioning will increase as the stacking height increases. If the acceptable degree of re-positioning can be defined (e.g. 30% additional moves), as well as the degree of uncertainty in the departure of containers from the stack, the optimum value of r_{st} can be found through computation or simulation. The uncertainty of departure depends, among other things, on the mode of through transport. Rail and IWT can generally be programmed rather well, in contrast with road transport.

The occupancy m_c has to be introduced because the pattern of arrivals and departures of containers is stochastic by nature. The optimum value of m_c depends on the frequency distribution of these arrivals and departures, and on the acceptable frequency of occurrence of a saturated stack. The number of container departures per unit of time may be more or less constant, at least for large terminals, but the number of arrivals is not. The container arrival distribution can have different forms and depends, in its turn, on the vessel arrival distribution and on the variation of the number of containers per vessel.

The gross surface area A_{TEU} per ground slot (including traffic lanes in the stack) is expressed in Twenty-feet Ground Slots (TGS). It is empirically established and depends on the handling equipment. NB: when looking at TGS stacking height is no longer relevant. Table 4.16 gives some typical values.

Gross TGS area	
Reach Stacker (RS)	18.0 m^2
Rubber Tired Gantry (RTG)	18.0 m^2
Rail Mounted Gantry (RMG)	18.7 m^2
Straddle Carrier (SC)	27.4 m^2

Table 4.16: Gross TGS area for different stacking equipment (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 4.33 illustrates the reason for the differences between the various types of equipment. The additional space that a RMG-stack requires over the RS- and RTG-stacks is associated with the space occupied by the rails. The main reason that a SC-stack needs a larger gross TGS area is that a SC needs space between the container rows to manoeuvre.

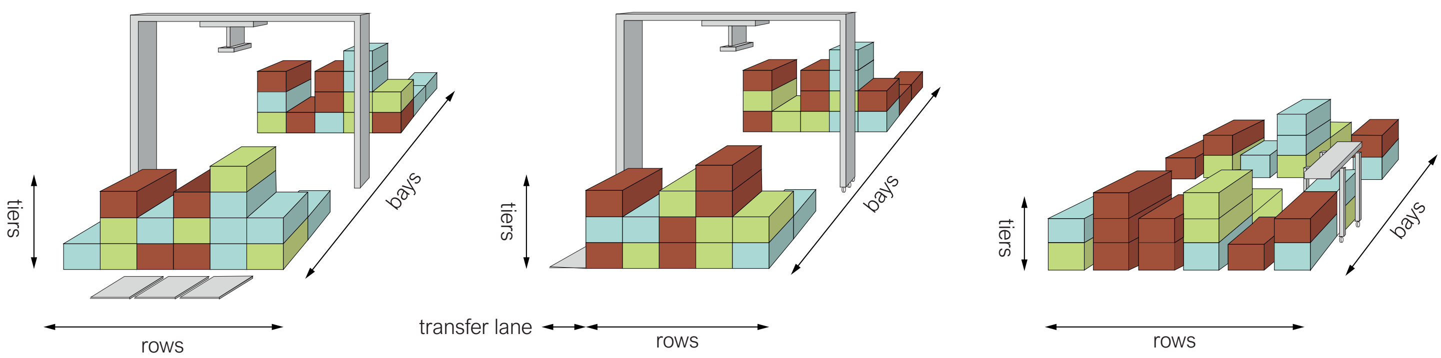


Figure 4.33: Block structures stacking equipment. Panel 1 (transfer bays in front) and 2 (transfer lane to the side) can be seen with RMG and RTG equipment, Panel 3 is typical for SC equipment (reworked from Böse, 2011, by TU Delft – Ports and Waterways is licenced by CC BY-NC-SA 4.0).

Part IV – Section 3.1 elaborates an example that illustrates the effect of container terminal equipment selection. For our current example we assume that SCs are selected as stack equipment of choice.

Ladens The majority of the container throughput will generally be ladens. In the example we assume straddle carriers to be used for their stacking. Using the input from Table 4.8, Table 4.16 and Equation 4.8 we can calculate the number of stacks required and the area that needs to be allocated to this.

Quantity	Symbol	Magnitude	Units
Gross ground slot area for SC	A_{TEU}	27.4	m^2/tgs
Throughput of ladens	C_{laden}	1,127,910	TEU/year
Peak factor for ladens	f_p	1.2	–
Average dwell time	$t_{d,av}$	7.5	days
Number of operational days	d_{yr}	358	days/year
Nominal stacking height	$H_{n,st}$	4	TEU-heights
Stacking width	W_{st}	45	TEU-widths
Stacking length	L_{st}	20	TEU-lengths
Average stacking fraction	r_{st}	0.8	–
Occupancy rate	m_c	0.7	–

Table 4.17: Basic data: ladens (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Quantity	Operation	Magnitude	Units
Total slots required	N_{tgs}	12,659	tgs
Total capacity required	$N_{tgs} \cdot H_{n,st} = C_{req}$	50,636	TEU
Total ground slots per stack	$W_{st} \cdot L_{st} = N_{tgs,st}$	900	tgs/stack
Total capacity per stack	$N_{tgs,st} \cdot H_{n,st} = C_{st}$	3,600	TEU/stack
Gross area per stack	$N_{tgs,st} \cdot A_{TEU} = A_{st}$	24,660	m^2/stack
Number of stacks required	$\text{ceil}(C_{req}/C_{st}) = N_{st}$	**15**	**stacks**
Total storage area for ladens	$A_{st} \cdot N_{st} = A_{ladens}$	**369,900**	$\mathbf{m^2}$

Table 4.18: Results: ladens (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 4.34: Example: ladens stack operated by straddle carriers (aerial imagery by the National Georegister (NGR) is licenced under CC BY 4.0).

Reefers We can apply the same procedure for the reefers, but here we have to take another factor into account, viz. the stack reefer factor, which is a combination of the TEU-factor and a multiplier for the reefer rack. It is a way to translate the FGSs, since reefers are often 40 ft long, to required surface area using the estimate A_{TEU}.

Quantity	**Symbol**	**Magnitude**	**Units**
Gross ground slot area for SC	A_{TEU}	27.4	m^2/tgs
Throughput of reefers	C_{reefer}	161,130	TEU/year
Peak factor for reefers	f_p	1.2	–
Average dwell time	$t_{d,av}$	6.5	days
Number of operational days	d_{yr}	358	days/year
Nominal stacking height	$H_{n,st}$	4	TEU-heights
Stacking width	W_{st}	22	TEU-widths
Stacking length	L_{st}	4	TEU-lengths
Average stacking fraction	r_{st}	0.8	–
Occupancy rate	m_c	0.7	–
Stack reefer factor	f_{reef}	2.35	–

Table 4.19: Basic data: reefers (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Quantity	**Operation**	**Magnitude**	**Units**
Total slots required	N_{tgs}	1,567	tgs
Total capacity required	$N_{tgs} \cdot H_{n,st} = C_{req}$	6,269	TEU
Total ground slots per stack	$W_{st} \cdot L_{st}/2 = N_{fgs,st}$	44	fgs/stack
Total capacity per stack	$2 \cdot N_{fgs,st} \cdot H_{n,st} = C_{st}$	352	TEU/stack
Gross area per stack	$N_{fgs,st} \cdot f_{reef} \cdot A_{TEU} = A_{st}$	2833.2	m^2/stack
Number of stacks required	$\text{ceil}(C_{req}/C_{st}) = N_{st}$	**18**	**stacks**
Total storage area for reefers	$A_{st} \cdot N_{st} = A_{reefers}$	**50,997**	$\mathbf{m^2}$

Table 4.20: Results: reefers (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 4.35: Example: reefers stack operated by straddle carriers (aerial imagery by the National Georegister (NGR) is licenced under CC BY 4.0).

Empties For empties and OOGs we follow a similar calculation procedure as for ladens and reefers, be it that the average stacking factor is equal to 1 in both cases and a different value for A_{TEU} is used (associated with different handling equipment). Furthermore the dwell time $t_{d,av}$ of empty containers is typically large.

Figure 4.34, Figure 4.35, and Figure 4.36 respectively depict loaded-, reefers-, and empties stacks.

Quantity	Symbol	Magnitude	Units
Gross ground slot area for SC	A_{TEU}	16.7	m^2/tgs
Throughput of empties	$C_{empties}$	306,147	TEU/year
Peak factor for empties	f_p	1.2	–
Average dwell time	$t_{d,av}$	11	days
Number of operational days	d_{yr}	358	days/year
Nominal stacking height	$H_{n,st}$	6	TEU-heights
Stacking width	W_{st}	35	TEU-widths
Stacking length	L_{st}	24	TEU-lengths
Average stacking fraction	r_{st}	1	–
Occupancy rate	m_c	0.8	–

Table 4.21: Basic data: empties (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Quantity	Operation	Magnitude	Units
Total slots required	N_{tgs}	2,352	tgs
Total capacity required	$N_{tgs} \cdot H_{n,st} = C_{req}$	14,110	TEU
Total ground slots per stack	$W_{st} \cdot L_{st} = N_{tgs,st}$	840	tgs/stack
Total capacity per stack	$N_{tgs,st} \cdot H_{n,st} = C_{st}$	5040	TEU/stack
Gross area per stack	$N_{tgs,st} \cdot A_{TEU} = A_{st}$	14,028	m^2/stack
Number of stacks required	$\text{ceil}(C_{req}/C_{st}) = N_{st}$	**3**	**stacks**
Total storage area for empties	$A_{st} \cdot N_{st} = A_{reefers}$	**42,084**	**m^2**

Table 4.22: Results: empties (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 4.36: Example: empties stack operated by empty handlers (aerial imagery by the National Georegister (NGR) is licenced under CC BY 4.0).

OOGs The gross ground slot area for OOGs deviates from that for the other container types. OOGs are often transported and stored on carrier chassis, which means that the ground slot is the parking area needed for the chassis (roughly 16 x 4 m), rather than the TEU-slot. If the OOGs are handled with a reach stacker, a similar space is required.

Quantity	**Symbol**	**Magnitude**	**Units**
Gross ground slot area for SC	A_{TEU}	64	m^2/tgs
Throughput of OOG's	$C_{OOG's}$	16,113	TEU/year
Peak factor for OOG's	f_p	1.2	–
Average dwell time	$t_{d,av}$	7	days
Number of operational days	d_{yr}	358	days/year
Nominal stacking height	$H_{n,st}$	1	TEU-heights
Stacking width	W_{st}	10	TEU-widths
Stacking length	L_{st}	10	TEU-lengths
Average stacking fraction	r_{st}	1	–
Occupancy rate	m_c	0.8	–

Table 4.23: Basic data: OOG's (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Quantity	**Operation**	**Magnitude**	**Units**
Total slots required	N_{tgs}	473	tgs
Total capacity required	$N_{tgs} \cdot H_{n,st} = C_{req}$	473	TEU
Total ground slots per stack	$W_{st} \cdot L_{st} = N_{fgs,st}$	100	tgs/stack
Total capacity per stack	$N_{tgs,st} \cdot H_{n,st} = C_{st}$	100	TEU/stack
Gross area per stack	$N_{tgs,st} \cdot A_{TEU} = A_{st}$	6,400	m^2/stack
Number of stacks required	$\text{ceil}(C_{req}/C_{st}) = N_{st}$	**5**	**stacks**
Total storage area for OOG's	$A_{st} \cdot N_{st} = A_{OOG's}$	**32,000**	$\mathbf{m^2}$

Table 4.24: Results: OOG's (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Stacking yard summary The gross slot areas include room for traffic of transport equipment, but that is within the stack. As an estimate, an additional 20% is taken into account for roads around the stacks.

Container type	**Nr. of stacks**	**Area per stack [m^2]**	**Total area [m^2]**
Ladens	15	24,660	369,900
Reefers	18	2,833.2	50,997
Empties	3	14,028	42,084
OOG's	5	6,400	32,000
Total area stacks			**494,981**
20% extra for roads			98,996
Total area storage yard			**593,977**

Table 4.25: Storage yard summary (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The 'throughput – storage yard area' ratio of this terminal is approximately 41,500 TEU/ha. It is interesting to compare this ratio with other terminals. Singapore, for instance, has 22,000 TEU/ha, and Hongkong 40-50,000 TEU/ha. The differences are mainly caused by differences in the efficiency of the storage yard and the dwell time. To shorten the dwell time, the stevedoring company must introduce incentives for shorter dwell times and penalties for longer dwell times than average, for instance by applying a variable tariff.

4.4.7 Step 7: Storage to hinterland transport

Container transport to and from the hinterland goes by road, by rail or over water, or by a combination of these. As an illustration, Figure 4.37 shows the recent evolution of this modal split for the port of Rotterdam. Although transport by road is still the largest fraction, growth (25% in total) mainly takes place in IWT (+ 48%) and rail transport (+ 40%)

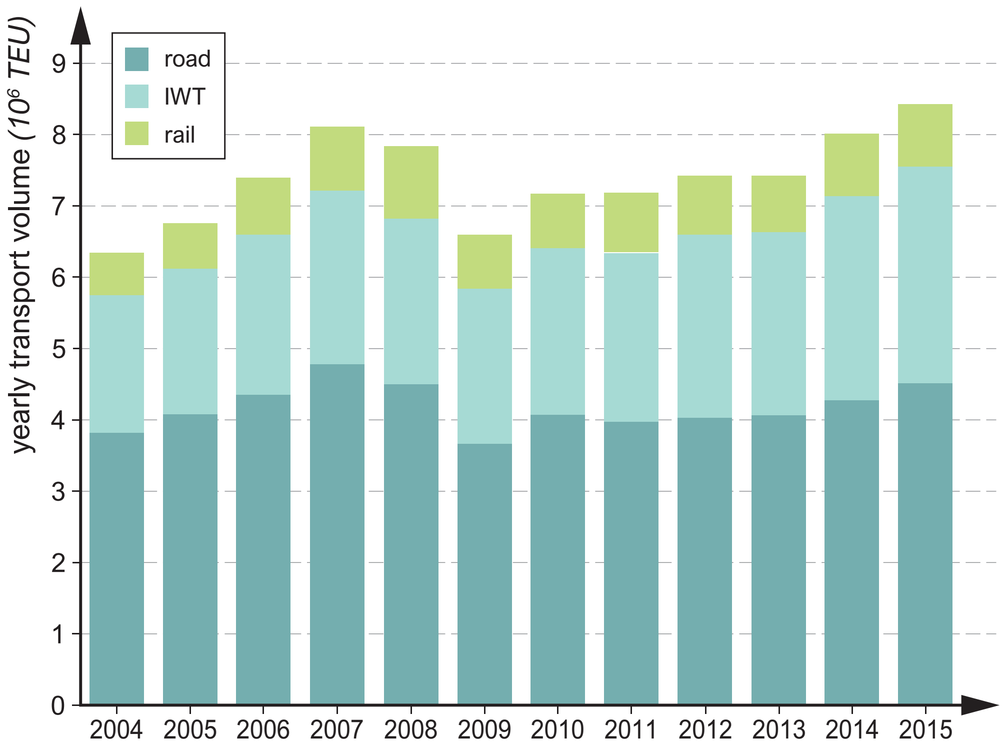


Figure 4.37: Modal split for container transport via the port of Rotterdam (by Monitor logistiek & Goederenvervoer voor Nederland 2016 is licenced under CC0 1.0).

Gate Trucks bringing or collecting containers enter and leave the terminal through the gate. Here three functions are executed:

- Administrative formalities related to the cargo, including customs inspection and clearance;
- Inspection of the boxes themselves (for possible damage); and
- Direction of the drivers to the location in the container transfer area.

The gate used to create long queues, due to the distinct peaks in the truck arrivals during the day. The introduction of electronic data processing and automated inspection of the boxes has shortened the delays at the gate considerably. Moreover, gates are presently designed for (statistically) the busiest hour of the year, such that waiting times can be kept within reasonable bounds (further see Section 4.3.4).

In the calculation example below we assume the transport to and from the hinterland to be exclusively by road. This means that the entire import and export throughput (369,000 and 393,600 TEU/year, respectively, see Table 4.7) has to pass by the road gate. We assume the TEU-factor to be 1.6, again.

import		export	
TEU/year	boxes/year	TEU/year	boxes/year
369,000	230,625	393,600	246,000

Table 4.26: Cargo flow specification (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Assuming one box per truck, the number of terminal exit and entry moves per year is equal to the number of import and export boxes per year, respectively. The peak load of a gate is calculated from:

$$M_{max} = M_y \cdot pf_{week} \cdot pf_{day} \cdot pf_{hour} / n_w \tag{4.9}$$

in which:

M_{max}	= peak number of moves per hour,
M_y	= number of moves per year,
pf_{week}	= peak factor for the busiest week of the year,
pf_{day}	= fraction of peak week moves at peak day.
pf_{hour}	= fraction of peak day moves at peak hour.
n_w	= number of operational weeks.

Then the design time required for gate operations follows from:

$$t_{d,g} = M_{max} \cdot \text{reloading fraction} \cdot \text{inspection time} \cdot \text{design capacity} \tag{4.10}$$

for exit and entry moves separately. The reloading percentage indicates which part of the trucks entering loaded will be reloaded and leave the terminal loaded, again. Trucks leaving empty are assumed not to need checking at the gate. The design capacity is the fraction of M_{max} for which the terminal is designed. This fraction is usually rather high (0.95 – 1.0). Once the required time for gate operation, $t_{d,g}$, is estimated, the number of required gates can be derived by taking the next higher integer of $t_{d,g}$/gate service time.

Table 4.27 provides some basic data that we can use in our current example. Table 4.28 shows how many entry and exit gates are needed to accommodate the export and import volumes respectively.

Quantity	**Symbol**	**Magnitude**	**Units**
Peak-week factor	pf_{week}	1.2	–
Peak-day percentage	pf_{day}	0.25	week/day
Peak-hour percentage	pf_{hour}	0.125	day/hr
Number of operational weeks	n_w	51.1	weeks/yr
Reloading fraction		0.75	–
Entry inspection time		1	min/move
Exit inspection time		2	min/move
Design capacity		0.98	–
Gate service time		60	min/hr

Table 4.27: Basic data: Gates (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Entry (handling export box moves)			**Exit (handling import box moves)**		
M_{max}	180	moves/hr	M_{max}	169	moves/hr
$t_{d,g}$	133	min/hr	$t_{d,g}$	249	min/hr
Nr. entry gates	**3**	**gates**	**Nr. exit gates**	**5**	**gates**

Table 4.28: Results: Gates (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 4.38 shows an example of a gate. Once through the gate the trucks take their assigned position at the container transfer area. For container imports this area is usually located immediately behind the import stacks and the truck's position is chosen to minimise the distance to the import containers to be picked up. For container exports the trucks bring their containers straight to the export stacks, where they are picked up by the stack equipment for placement in the designated stack.

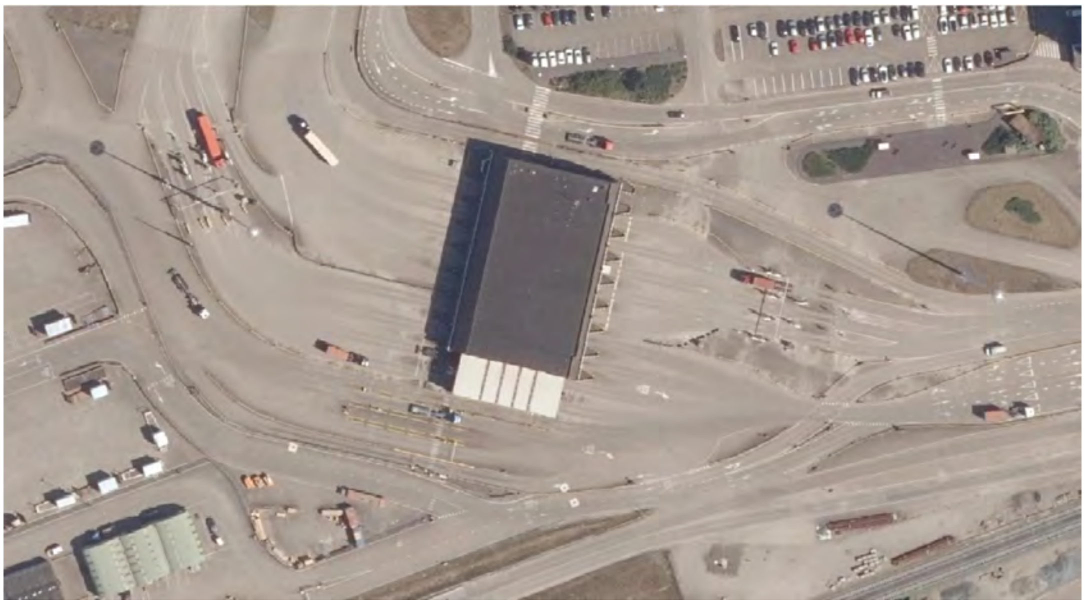


Figure 4.38: Example: road gates (aerial imagery by the National Georegister (NGR) is licenced under CC BY 4.0).

IWT terminal Dimensioning of an IWT-terminal follows a similar procedure as already described in design Steps 2, 3 and 4: once the amount of cargo to be shipped via IWT and the associated vessel mix are known, a berth configuration can be designed for a desired minimum service level. IWT container vessels are typically much smaller than their sea-going counterparts. As a result smaller (un)loading equipment is involved, which in turn leads to lower (un)loading capacities. Depending on the modal split, and the resulting cargo volume that needs to be shipped over water into the hinterland, a large number of IWT-vessels may be involved. The ever-increasing sea-going container ships can deliver a huge supply of containers at once. This causes peaks in the number of containers that arrive at a terminal, which can make their timely departure to the hinterland challenging. Congestion problems associated with this are not uncommon. Due to the many similarities we will not present a quantified design of the IWT-terminal in this example. Figure 4.39 gives an example of an IWT-quay (on the right), adjacent to the sea-shipping quay (on the left).

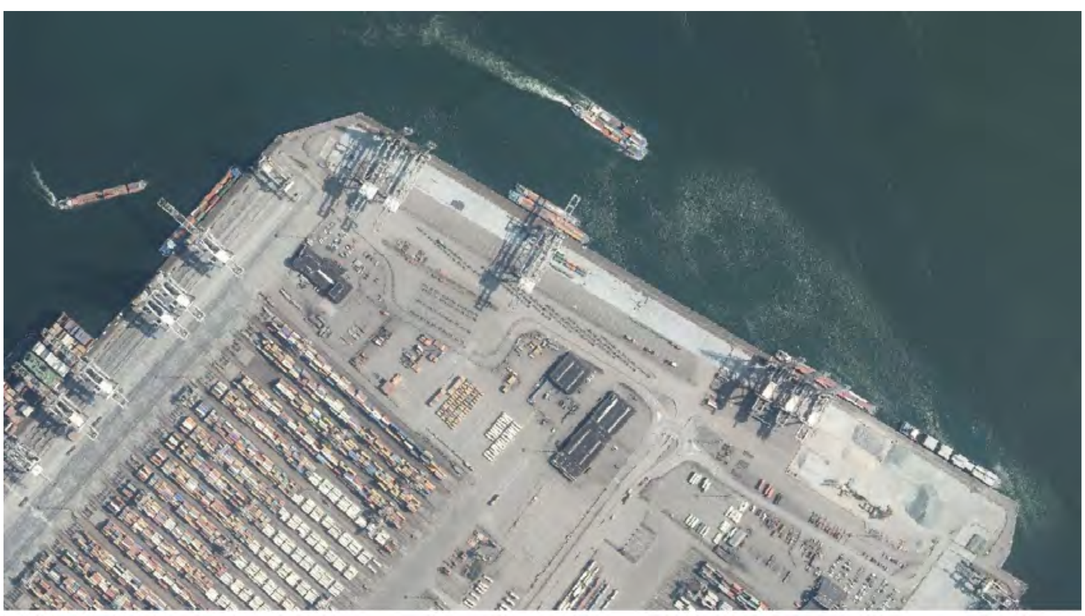


Figure 4.39: Example: IWT-quay, part of a larger container terminal (aerial imagery by the National Georegister (NGR) is licenced under CC BY 4.0).

Rail terminal Hinterland transport via rail can be done via on-terminal as well as via off-terminal rail stations. The rail terminals outside the container terminal are also called RSCs. Both on- and off-terminal the formation of so-called block trains, i.e. wagons which all have the same hinterland destination, will be promoted. Transfer from the container terminal to the RSC is done by trailer, which passes via the gate. On modern terminals an internal road may connect to the RSC, allowing use of terminal equipment such as MTS.

The layout of these RSCs falls outside the scope of this book. However, by-enlarge a functional design of a rail terminal can be derived in a similar manner as for quays and gates. Based on the amount of cargo that a rail station should be able to handle, and a given maximum train length, you can derive the number of tracks that should be installed to conform to a given performance criterion. The train length times the track width and the number of tracks provides a first order estimate of the surface area required. Figure 4.40 gives an example of a rail terminal. In this case 4 tracks of approximately 750 m long have been implemented.

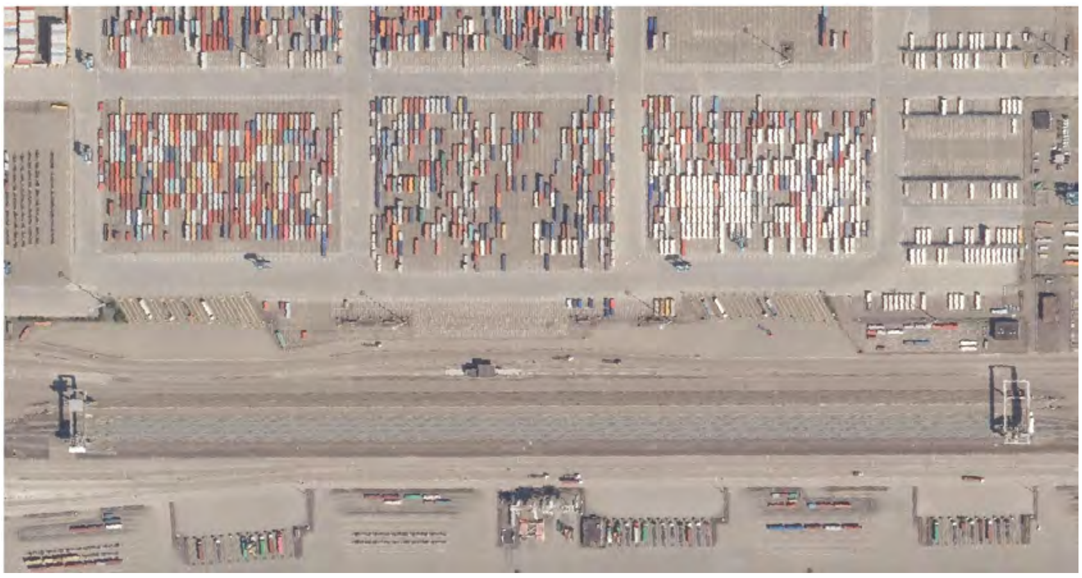


Figure 4.40: Example: rail terminal (aerial imagery by the National Georegister (NGR) is licenced under CC BY 4.0).

4.4.8 Step 8: General services

There is a range of general services that belong to a container terminal. We briefly discuss the so-called Container Freight Station (CFS) and a number of 'other facilities'.

Container Freight Station (CFS) Sometimes cargo imported in one container has different inland destinations. This means that it has to be redistributed at the terminal ("stripping"). Similarly, export cargo from different inland sources may have to be packed in one container ("stuffing"). After an import container has been stripped and before an export container is stuffed, the cargo is stored in the so-called Container Freight Station (CFS). In some cases the CFS and/or the empties yard are located outside the terminal property. The surface area of the CFS, A_{cfs}, is calculated from:

$$A_{cfs} = \frac{N_c \cdot V \cdot t_d \cdot f_{area} \cdot f_{bulk}}{h_c \cdot m_c \cdot 365} \tag{4.11}$$

in which:

N_c = number of TEU moved through the CFS [TEU/yr], (also called Less than Container Load (LCL)),
V = contents of 1 TEU container with the average capacity of 90% (= 0.9 times the available capacity of 32 m^3 = 29 m^3),
t_d = average dwell-time [d],

f_{area} = ratio of gross and net area [-] (accounting for internal travel lanes and containers),
f_{bulk} = bulking factor [-],
h_c = average height of cargo in the CFS [m],
m_c = acceptable occupancy rate [-],

The containers are positioned around the CFS during actual transfer of cargo, which is also reflected in the value of f_{area} (≈ 1.4). The factor f_{bulk} accounts for additional space needed for cargo requiring special treatment or repairs. One often finds values of 1.1 – 1.2. The factor m_c again reflects the random character of arrivals and departures of this cargo, and the need to avoid a full CFS. Normal values are 0.6 – 0.7. At large container terminals less and less CFS facilities are present. Therefore, we ignore it in the calculation example.

Other facilities Next to the quay wall and apron, the main container stack, and the hinterland facilities (road, IWT, rail) there is a range of other facilities that are generally part of a container terminal:

- general offices + parking space,
- one or more workshops,
- a repair building,
- parking space for trailers, and
- an area for scanning and inspection.

Rather than designing these to a similar detail as we did the other terminal elements, we will assume a set of surface area values for each component (see Table 4.29). The numbers are loosely based on obeservations derived from aerial photographs and an estimate that roughly 15% of the total terminal surface area consists of items other than the apron area and the storage yard.

General office + parking space	12,500	m^2
Workshop + parking space	20,000	m^2
Repair building + parking space	61,000	m^2
Trailer parking	30,000	m^2
Scanning and inspection area	2,700	m^2
Total	**126,200**	$\mathbf{m^2}$

Table 4.29: Surface area estimates for other facilities (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

4.4.9 Step 9: Summary

In the previous steps we systematically investigated which terminal elements are involved in the handling of an annual throughput of 2,460,000 TEU at a minimum prescribed service level. Based on a range of explicitly stated assumptions we elaborated a functional design to derive the number of system elements required, and to estimate their order-of-magnitude dimension. Table 4.30 presents an aggregated summary of the main terminal elements and how they contribute to the overall surface area.

Quay length	1,600.1	m	
Apron area	131,207	m^2	15.4%
Storage yard	593,977	m^2	69.8%
Other facilities	126,200	m^2	14.8%
Total	**851,384**	$\mathbf{m^2}$	**100%**

Table 4.30: Total terminal surface area (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The apron area plus the storage yard surface area divided by the quay length yields the so-called 'terminal depth'. For this example this results in a terminal depth of 453 m. For a modern container terminal, this depth typically lies between 400 – 500 m. A value of 453 m gives some confidence that our terminal is of reasonable dimensions.

Systematically following the terminal design steps, as done above, provides valuable information that can feed back into the port layout process. Where layout efforts were first based on rough rule-of-thumb estimates, we now have a better picture of what kind of surface area is required to accommodate a desired annual throughput, and what kind of infrastructure this requires in terms of quay length, STS-cranes, tractor trailers, et cetera. It is good to realise that selecting a different type of terminal equipment can have significant effect on the required surface area. However, accommodating a given throughput on a smaller surface area, is generally offset with higher CAPEX associated with STS-cranes and more efficient yard equipment (see also Part IV – Section 3.1).

4.5 Developments

The container transport market is highly competitive. New technology is continuously developed, resulting in larger and more efficient vessels, more efficient terminals and consequently more container transport. In this process of ongoing competition and improvement, a number of recognisable developments can be identified.

4.5.1 Simulation models

Simulation is increasingly applied to container terminals worldwide. It enables consultants, designers and terminal operators to accomplish strategic and tactical planning related to existing and new-to-develop container terminals. Simulation models can be of use to:

- analyse and optimise the operation of existing terminals,
- develop a conceptual/functional design of a container terminal extension and/or a new terminal,
- identify and solve capacity bottlenecks;
- improve a terminal's performance and service level.

4.5.2 Terminal automation

Shipping lines are pressing terminals to increase their service level, and at the same time to reduce their handling costs. As labour expenses form a large part of the latter, automated container handling has proven to be an effective way to reduce operational costs of large terminals.

In terminal operations, automation is possible at three levels (Rademaker, 2007):

- *Level 1* – sharing information, i.e. electronic exchange of information between shipper, carrier, haulier, receiver and terminal operator.
- *Level 2* – planning and control of operational processes at the terminal. Automation at this level means using information systems for planning decisions and control of terminal operations.
- *Level 3* – the actual handling of containers, meaning partly or fully robotised operation of equipment.

An example of a large, fully automated terminal is the APMT terminal on Maasvlakte 2 (Figure 4.41), with a capacity of 2.7 million TEU per year. The terminal concept is based on using STS cranes, remotely operated from a central control room. They unload containers from the vessel and place them directly onto a fleet of Lift Automated Guided Vehicles (Lift AGVs). The Lift AGVs can carry two 20 ft containers at a time and shuttle them at a speed of 22 km/h from the quay to the container yard using an on-board navigation system that follows a transponder grid. Once the Lift AGV arrives at its programmed destination it lifts the containers onto storage racks. Next, an Automated Rail-Mounted Gantry (ARMG) crane (Figure 4.42) takes the container from the rack to its designated location in the stack (APM-Terminals, 2012).

Figure 4.41: Overview of the container terminal AMPT Maasvlakte 2 (APM Terminals MVII: 2018 by APM Terminals is licenced under CC BY-NC-SA 4.0).

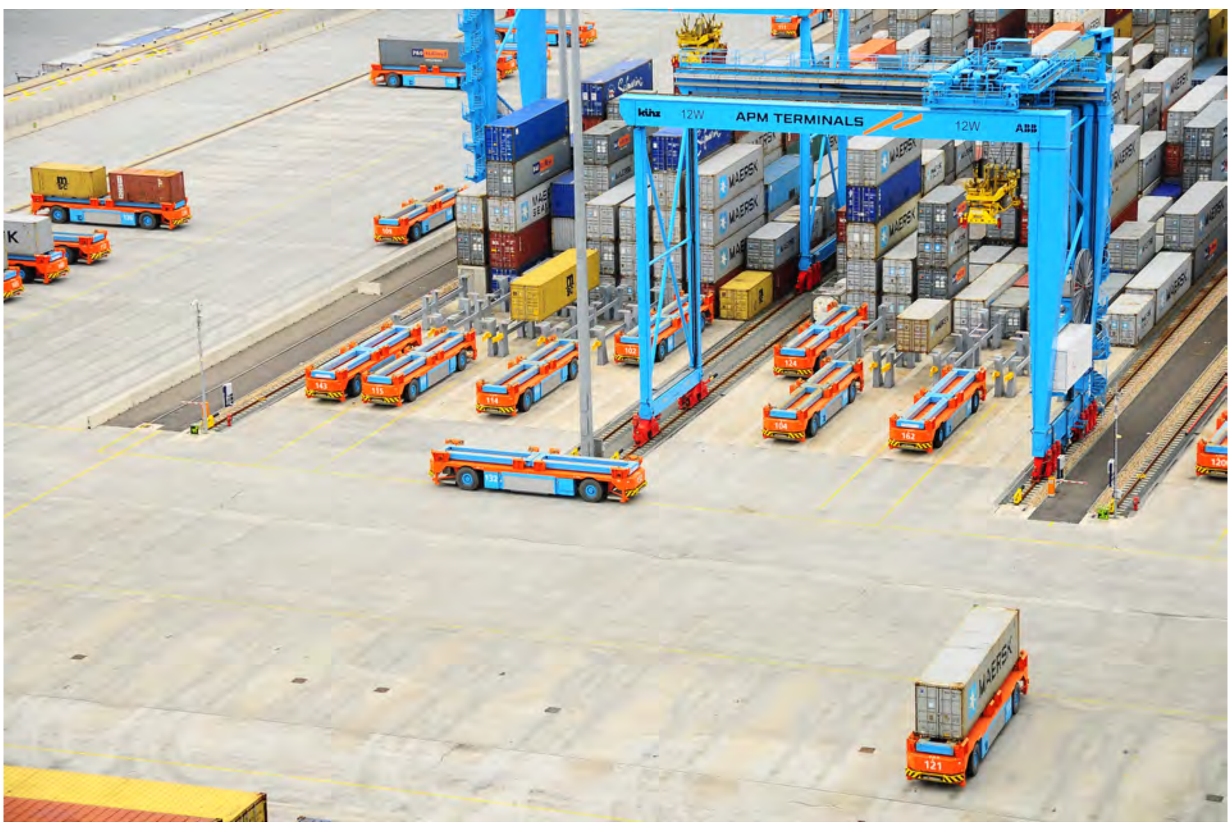


Figure 4.42: ARMG and truck transfer docks, AMPT Maasvlakte 2 (APM Terminals Maasvlakte II, Rotterdam by APM Terminals is licenced under CC BY-NC-SA 4.0).

Another example of a fully automated terminal is Altenwerder Container Terminal in Hamburg, Germany. It became operational in 2002 (Figure 4.43).

Figure 4.43: Overview of the container terminal Altenwerder, Hamburg, Germany (Phb dt 8107 CTA by Dirtsc is licenced under CC BY-SA 3.0).

4.5.3 Terminal Operating System (TOS)

Maximising terminal performance and operational efficiency can hardly be done without a computerised Terminal Operating System (TOS). Terminal operators use the information from a TOS to optimise the use of equipment at the quayside and in the container yard. It can also help managing the terminal's business transactions, including gate operations, invoicing, finance, accounting and management reports.

A real-time TOS provides up-to-date information on events throughout the terminal, including data on productivity and time lost on cranes or in the yard. With this information planners can quickly and easily determine vessel loading/unloading plans and the best allocation of manpower, equipment and yard space. A real-time TOS also enables an immediate response to exceptional events and accidents.

The TOS can help minimise unused yard space, unnecessary container and equipment moves, lost containers and excessive dwell times. Detailed graphic visualisation enables real-time monitoring of berth space, vessel stowage and equipment activity, thus allowing to change operations if necessary.

The TOS can automatically assign gangs and cranes to vessels, sequence the cranes and track their productivity real-time. It can also predict vessel loading and unloading times and can alert the operator to factors relevant to the service commitment, such as time-sensitive customer delivery or transhipment to another vessel.

The system can usefully generate an automated stowage plan and will consider the trade-off between vessel and yard efficiency, such as the impact of RMG/RTG crane movements and lane changes and the effects of retrievals from more remote parts of the container yard.

TOS-supported yard planning and control can include:

- a detailed yard model and real-time views,
- utilisation and maintenance reporting,

- flexible allocations for yard planning and equipment utilisation,
- automated tracking and notification of planning errors.

TOS-supported vessel planning and control can include:

- advanced stowage validation,
- real time tracking of vessel planning execution.

Last, but not least, the TOS gives access to a wealth of very detailed historical data. This data can be most useful for layout and operational rearrangements of the terminal.

4.5.4 Security

A new comprehensive security regime came into force in July 2004 with the intention of strengthening maritime security to prevent and suppress acts of terrorism against shipping. Both the International Ship and Port Facility Security (ISPS) Code and the Container Security Initiative (CSI) have represented the culmination of work by the IMO's Maritime Safety Committee and the United States Custom and Border Protection Service in the aftermath of terrorist atrocities in the United States in September 2001.

The ISPS Code takes the approach that the security of ships and port facilities is basically a risk management activity. To determine what security measures are appropriate, a risk assessment must be undertaken for each particular case.

Container movements are considered particularly sensitive in this respect, and are therefore subject to some specific regulations. In particular the CSI seeks to use Non-Intrusive Inspections (NII) and radiation detection technology before containers are shipped to the United States of America.

The ISPS Code was adopted by the IMO on July 1^{st} 2004 as an amendment of the International Convention for the Safety of Life at Sea (SOLAS). The objectives of the ISPS Code (NeRF-Maritime, 2004) are:

- to establish an international framework involving contracting governments, government agencies, local administrations and the shipping and port industries to detect security threats and take preventive measures against security incidents affecting vessels and port facilities used in international trade;
- to establish the respective roles and responsibilities of the contracting governments, government agencies, local administrations and the shipping and port industries, at the national and international level, for ensuring maritime security;
- to ensure the early and efficient collection and exchange of security-related information;
- to provide a methodology for security assessments so as to have in place plans and procedures to react to changing security levels;
- to ensure confidence that adequate and proportionate maritime security measures are in place.

In order to achieve its objectives the ISPS Code embodies a number of functional requirements. These include but are not limited to the following:

- gathering and assessing information with respect to security threats and exchanging such information with appropriate contracting governments;
- requiring the maintenance of communication protocols for vessels and port facilities;
- preventing unauthorised access to vessels, port facilities and their restricted areas;
- preventing the introduction of unauthorised weapons, incendiary devices or explosives to vessels or port facilities;
- providing means for raising the alarm in reaction to security threats or security incidents;
- requiring vessel and port facility security plans based upon security assessments;
- requiring training drills and exercises to ensure familiarity with security plans and procedures.

Under CSI, high-risk containers receive security inspections, including X-ray and radiation scans (Figure 4.44), before being loaded on board vessels destined for the USA. Once high-risk containers are inspected at CSI ports, they are not ordinarily inspected again upon arrival at the US seaport. This means that the containers inspected at CSI ports actually move faster, more predictably and efficiently through USA seaports.

Figure 4.44: Fast Scan Vehicle and Container inspection system ("Douane Vervoer Controle" by Willem van Kasteren is licenced under CC BY-SA 4.0).

5 Other terminal types

[1]As mentioned in Chapter 3, there are many types of other terminals, apart from container terminals. Each of these has its own specific design requirements and operational procedures. In this chapter we will briefly summarise the most important aspects of a number of these other terminals. The reader is referred to Ligteringen (2017) and the relevant PIANC manuals for more detail.

5.1 Liquid bulk terminals

Liquid bulk refers to cargo that is unpackaged and in liquid form. It can be crude oil, oil products, chemical products, vegetable oil and liquefied gases (LNG, LPG, hydrogen, et cetera). Important discriminating properties for shipping are the density and the temperature and pressure under which the material is transported. These three properties are mutually dependent, following the physical laws of Boyle and Gay-Lussac. Crude oil, which is transported under atmospheric pressure and temperature, has a density of $0.85 \div 0.97$ ton/m^3, liquefied gas of $0.4 \div 0.6$ ton/m^3, depending on temperature and pressure. Liquid hydrogen has a density of only 0.07 ton/m^3, but has to be transported at a very low temperature (-253°C). Clearly, these different types of liquid bulk put different demands on vessel designs and port facilities.

5.1.1 Oil terminals

Crude oil is won from onshore or offshore wells. It is transported from these upstream wells to the export terminal, where it is stored and loaded into crude carriers. These carriers transport the crude oil to overseas (downstream) import terminals, where it is stored for onward transport to a refinery (see Figure 5.1).

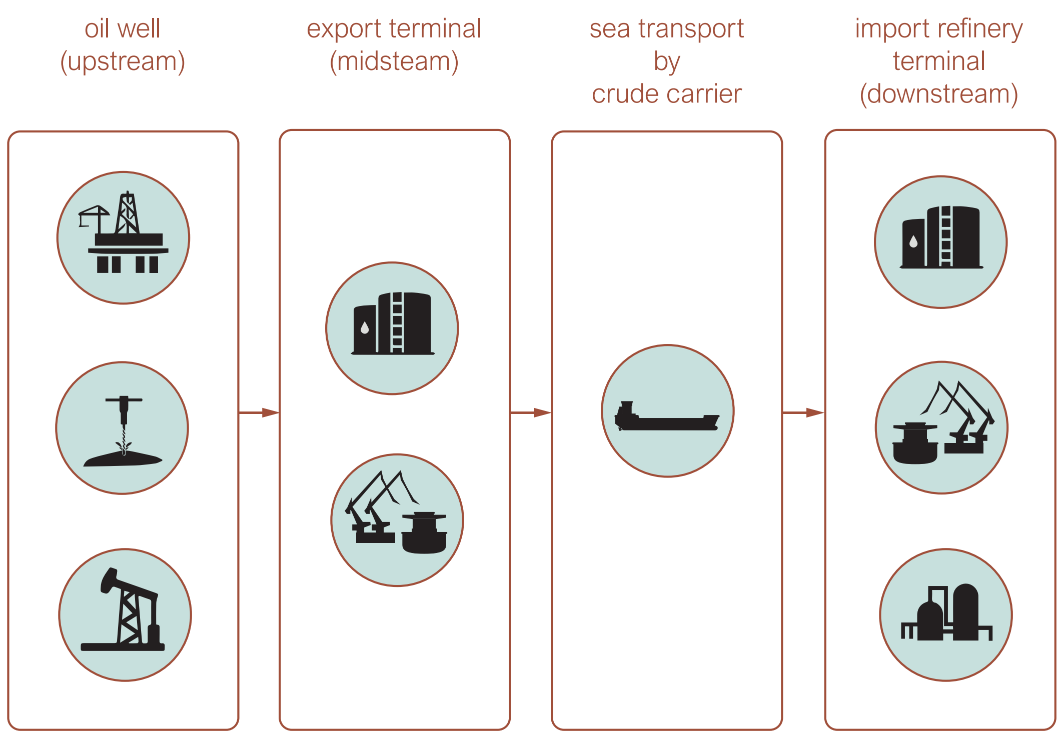


Figure 5.1: Schematic of a crude oil supply chain (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

[1]This chapter made use of lecture slides (Quist, 2019) for the Ports and Waterways course CIE5306 at TU Delft

Refining transforms the crude into a variety of oil products, which are subsequently distributed overseas by seagoing tankers, or to the hinterland through pipelines, or by barge, rail or truck. At the refinery the oil products can also be blended, by adding bio-ethanol, for instance.

Before focusing on the terminals (boxes two and four in Figure 5.1), we have to know more about the carriers. Like in the case of container vessels, the size of crude oil carriers has increased over the years. Figure 5.2 gives the most important characteristics of typical oil tanker classes.

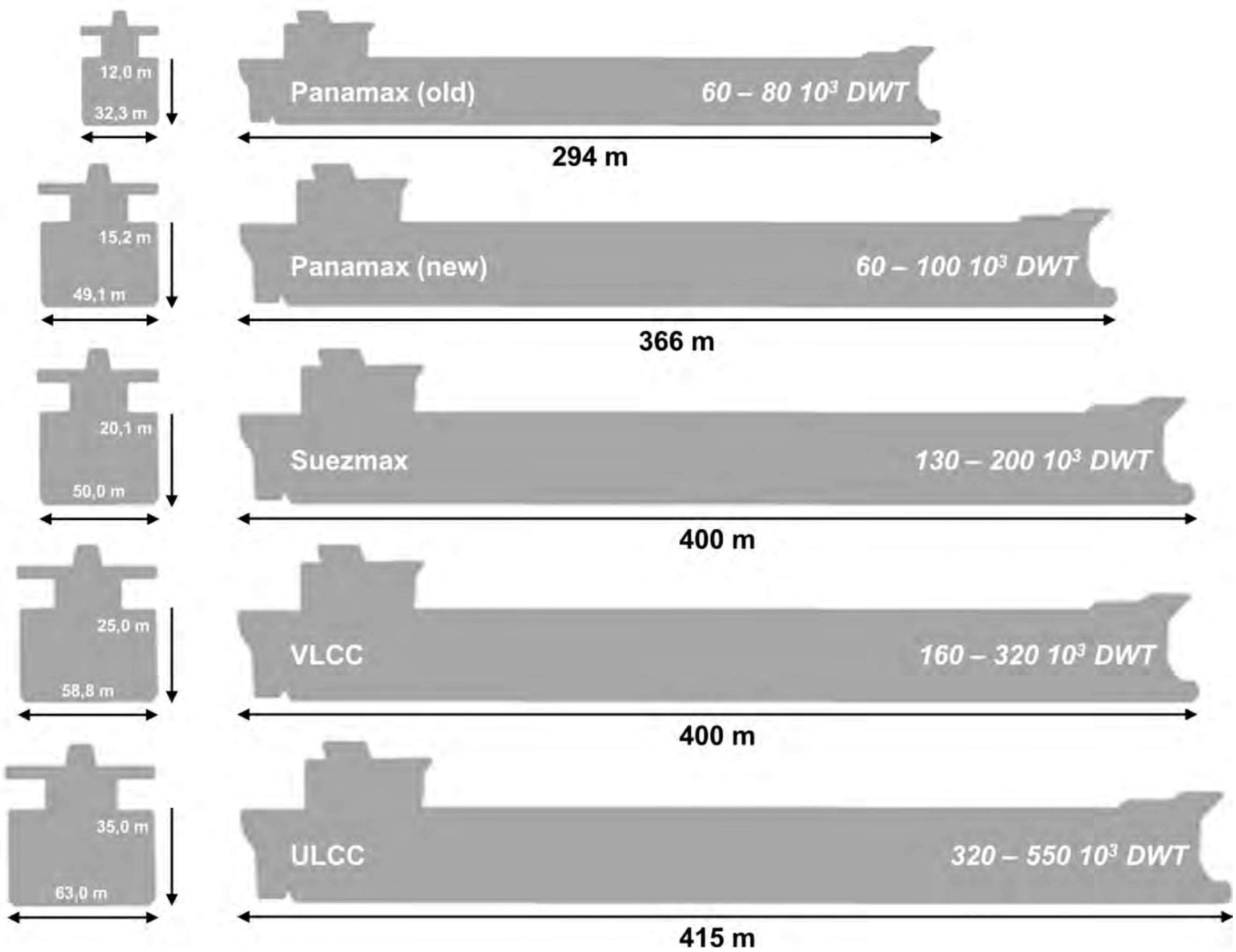


Figure 5.2: Typical oil tanker classes; lengths and widths are to scale, draughts are not (modified from Maximum ship sizes for the Panama and Suez canals, Strait of Malacca by U.S. EIA; Surveyor (2002); Maritime Connector is licenced under CC0 1.0).

The largest crude carrier ever built, the Seawise Giant with a capacity of 564,763 DWT and a length of more than 458 m (built in 1979), could not reach some major ports when fully loaded, was subsequently reduced to a permanently moored storage tank and has now been scrapped. Present-day ULCCs are not much longer than 400 m.

This illustrates that tanker dimensions are limited by the route taken. Vessels in the New Panamax class, for instance, are the largest that can pass Panama Canal, while the Suezmax class is dimensioned for the Suez Canal.

Liquid bulk cargo, crude oil, is generally loaded and unloaded via a manifold, which is placed midships and consists of a number of pipes, each connected with a different onboard storage tank (Figure 5.3, left). Loading and unloading takes place via one or more loading arms or flexible hoses connected to the manifold (Figure 5.3, right). This arrangement concentrates the points for loading and unloading, such that the equipment does not have to move alongside the ship. Consequently, the jetty or quay does not have to extend over the full length of the ship, a relatively small service platform is sufficient. It should be just large enough for the support of the marine loading arms and auxiliary facilities such as an operator's box, a gangway tower and firefighting equipment.

Figure 5.3: Liquid bulk (un)loading facilities; left: manifold (Maya OBO carrier 3 by Herv Cozanet is licenced under CC BY-SA 3.0); right: (un)loading arms (Marine Loading Arm KLEa by Ljl.kanon is licenced under CC BY-SA 3.0).

This is reflected in the design of the jetty, which only has to connect the service platform with the shore and provide the possibility for the ship to be safely moored. Figure 5.4 outlines a conventional jetty design, with a service platform, breasting dolphins to support the vessel and mooring dolphins to fasten the mooring lines. The shore connection consists of an access bridge and a pipe bridge connecting the loading arms or the hoses with the terminal storage tanks.

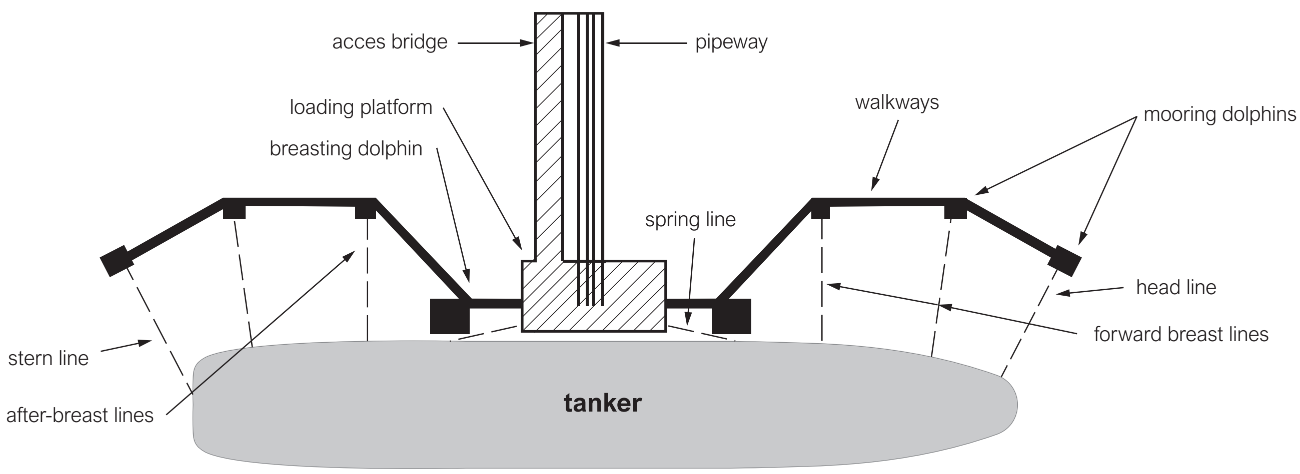


Figure 5.4: Conventional T-jetty design (modified from Thoresen, 2018, image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Next to the T-jetty shown in Figure 5.4, other conventional jetty types are the L-jetty (for a single vessel) and the finger jetty (for two vessels, see Figure 5.5, left). These conventional jetties are usually located in sheltered port basins and are characterised by a high loading and unloading capacity.

Another type of loading and unloading facility is buoy mooring, either to a single buoy or to multiple buoys. Buoy mooring can be applied at more exposed locations outside the port complex, as it can operate under higher wave conditions. A tanker attaches its mooring lines to the buoy system and a hose to the offloading buoy (Figure 5.5, right). Via a submerged pipeline the cargo is pumped to the onshore terminal and stored there. The advantage of a buoy system is that it can be located in deep water, such that a deep draught access channel to the port is not necessary. On the other hand, buoy systems generally have a lower capacity, more downtime and higher maintenance costs than a conventional jetty system.

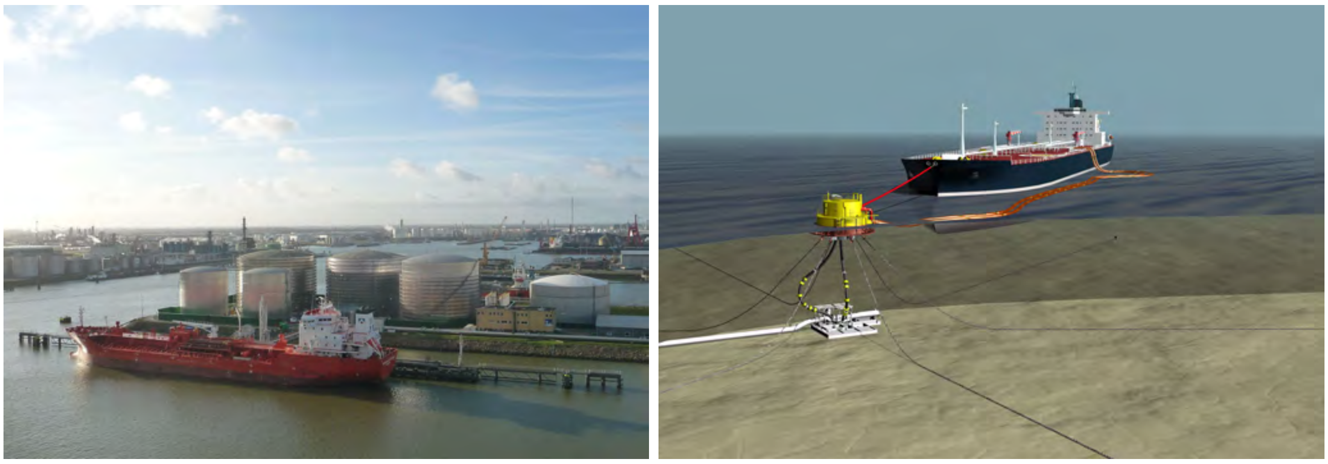


Figure 5.5: Tanker mooring arrangements; left: T-jetty mooring in Botlek, Rotterdam, the Netherlands (by BoH is licenced under CC BY-SA 3.0); right: single point buoy mooring (Functional SPM (Turret Buoy) by BluewaterPR is licenced under CC BY-SA 4.0).

Design objectives for an oil terminal are throughput, storage and safety, under the constraint of a limited waiting time for the vessels waiting to be served. Note, however, that tankers are not always waiting to be served: if the market collapses, like during the 2020 Corona pandemic, ships are just kept waiting for the right moment to put the cargo into the market.

One of the determining parameters in the design is the berth productivity, which can be estimated by:

$$C_b = p \cdot n_h \cdot n_d \cdot m_b \tag{5.1}$$

in which:

C_b	=	berth productivity [ton/year],
p	=	pump capacity [ton/hour],
n_h	=	number of operational hours per day [hours/day],
n_d	=	number of operational days per year [days/year],
m_b	=	berth occupancy [-].

In order to maintain sufficient pressure, shore-based pumps are used for loading, the tanker's pumps for unloading. VLCCs have typical pump capacity of 5,000 m^3/hr per pump, but have 3 pumps so in total 10,000 $m^3/hr \sim 15,000 m^3/hr$ for the largest vessel. The density of the product and pipeline sizing onshore has impact on the offloading capacity. As a rule of thumb the total tanker pump capacity is about 10% of the tanker's deadweight tonnage per hour. Normally, the maximum acceptable service time is 1 to 1.5 day, depending on the size. As a rule of thumb, the acceptable berth occupancy lies between 40% for a single berth and 80% for four berths. This may suffice as a first estimate in the early design phase, but later phases require more accurate calculations. A more detailed assessment of the required number of berths, unloading equipment and storage tanks can be made by following the steps described in Section 3.3.3 (see Section 4.4 for their application to a container terminal).

Safety is a special point of attention when designing liquid bulk terminals. In the case of oil, spills and fires are particular hazards. Apart from double-hull vessels, safety equipment and an operational safety regime, safety is also realised by applying safe distances between loading platforms, between berths and from navigation channels. In the storage area special precautions need to be taken, like sufficient distance between storage tanks, and a containment basin in case a tank starts leaking (required basin volume at least 1.1 times the volume of the largest tank). Figure 5.6 shows an aerial picture of containment bunds around oil storage tanks at the Maasvlakte Oil Terminal in the Port of Rotterdam.

Safe mooring is another point of attention in the terminal design. To that end, the Oil Companies International Forum developed the 'Mooring Equipment Guidelines' (OCIMF, 2018). Following these guidelines one can design

Figure 5.6: Containment bunds around oil storage tanks at the Maasvlakte Oil Terminal in the Port of Rotterdam (from www.vopak.com, Maasvlakte Olie Terminal (Rotterdam) by Vopak. Copyrights 2021 Royal Vopak.).

a safe and optimum mooring arrangement (Figure 5.7). The mooring lines are attached to bollards or quick release hooks (Figure 5.8, left) that are installed on top of the mooring and breasting dolphins. In this arrangement the spring lines are attached to mooring points on the deck of the loading platform. Breasting points are located within 0.25 ÷ 0.40 L_{OA} around the midship axis, in order to make sure that the breasting points are in the parallel body of the tanker. The breasting points can be integrated with the platform, but are often realised by separate breasting dolphins, so that in the event of overloading the platform with the expensive equipment on top of it remains undamaged.

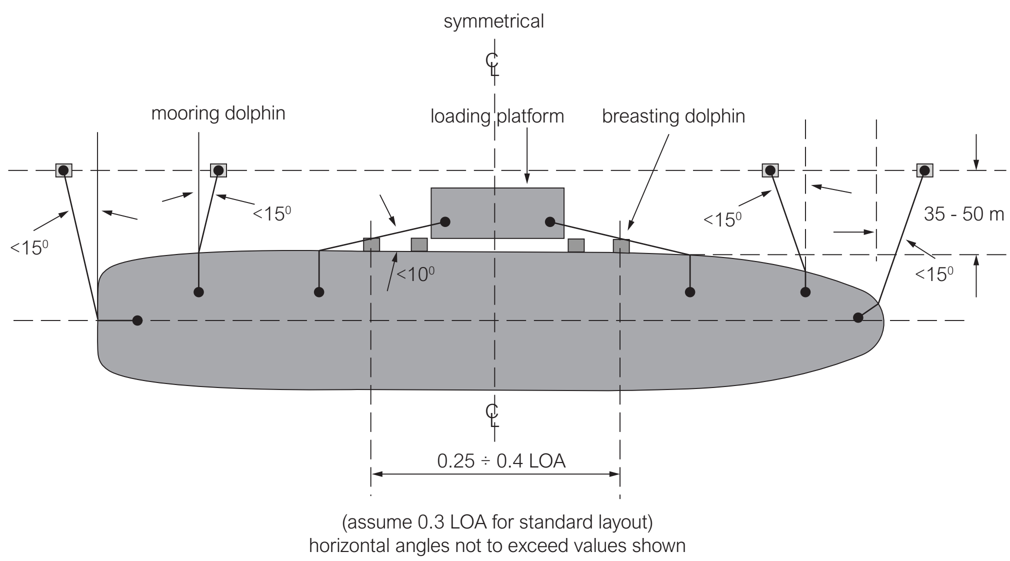


Figure 5.7: Optimal mooring arrangement for a liquid bulk carrier (reworked from OCIMF, 2018, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Apart from the mooring arrangement, fendering also contributes to safe berthing. An adequate fender plan is therefore a prerequisite for liquid bulk jetties. Installed on the breasting dolphins (Figure 5.8, left), the fenders support the tanker and absorb berthing energy by deformation. Normally jetties accommodate a range of tankers, so additional fender points may be required.

For further reading see also:

- PIANC (2012a) – PIANC Report N°116 “Safety Aspects Affecting the Berthing Operations of Tankers to Oil and Gas Terminals”
- PIANC (2016d) – PIANC Report N°153 “Recommendations for the design and assessment of marine Marine Oil and Petrochemical terminals”
- Ligteringen (2017) – “Ports and Terminals”, Chapter 10
- OCIMF (2018) – “Mooring Equipment Guidelines (MEG4)”

Figure 5.8: Mooring equipment; left: quick release hook; right: breasting point fender (source: Trelleborg catalogue safe berthing and mooring, 2008).

5.1.2 Gas terminals

The LNG supply chain has a certain similarity with the crude oil supply chain (Figure 5.9). Before being cost-effectively transportable the gas needs to be liquefied, which reduces its volume by a factor 600. This is done at a liquefaction plant, where the gas is liquefied by refrigeration and/or pressure. Under atmospheric pressure natural gas can only by liquefied by cooling it to a temperature around -163°C . The liquefaction plant and storage tanks are normally located at a marine export terminal where LNG tankers can berth and be loaded. The tankers transport the LNG to the overseas import terminal, where the cargo is unloaded and stored in LNG storage tanks. At the import terminal a re-gasification plant vaporises the LNG by heating it, for instance with warm water from a nearby power plant. After re-gasification the gas is added to the distribution system, often a pipeline system. Some LNG import terminals also have hinterland connections by truck, railway or IWT.

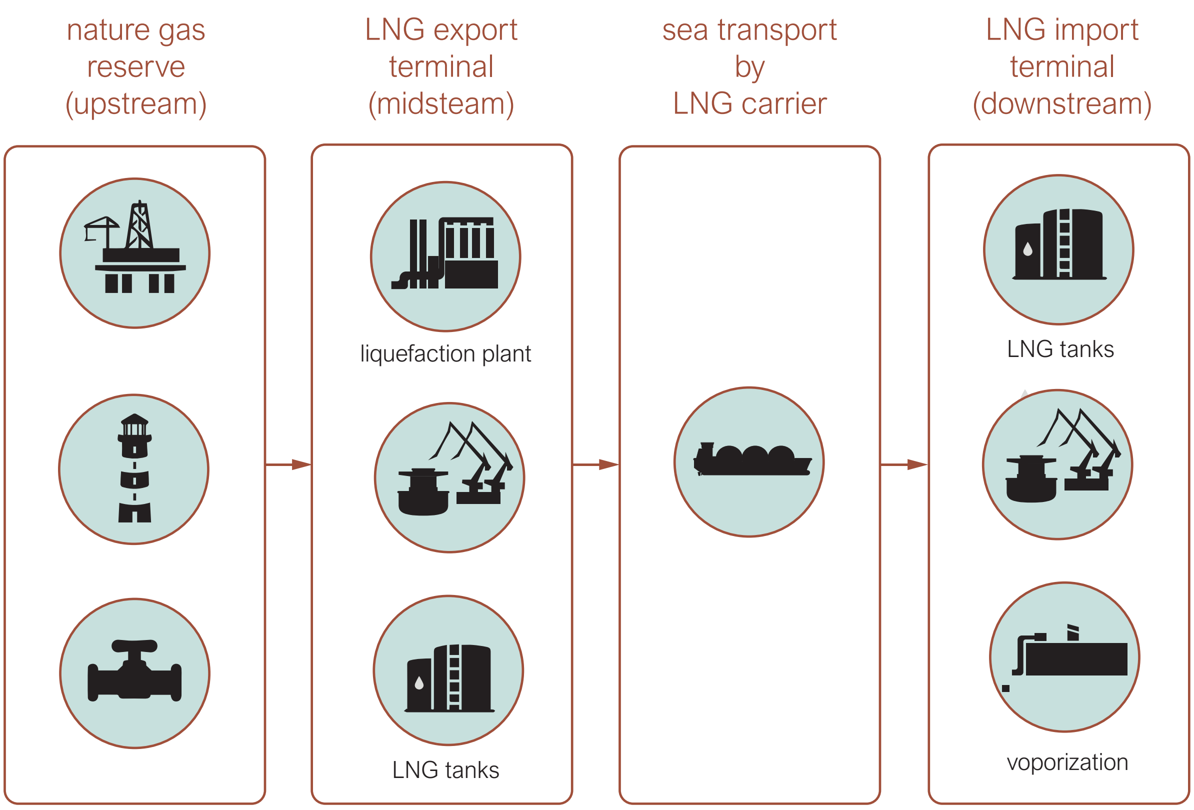


Figure 5.9: Schematic of the LNG supply chain (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Because of the lower density, LNG and LPG carriers have a smaller range of DWT and a higher freeboard, so more windage than crude carriers. Table 5.1 from Puertos del Estado (2007) gives an overview of their dimensions.

DWT (t)	Δ_m (t)	L_{oa} (m)	L_{pp} (m)	B (m)	T (m)	C_B (-)	Min. Lateral Windage: Fully Loaded (m^2)	Max. Lateral Windage: In Ballast (m^2)	Approx. Capacity (m^3)
LNG Carriers (Prismatic)									
125,000	175,000	345.0	333.0	55.0	12.0	0.78	8,400	9,300	267,000
97,000	141,000	315.0	303.0	50.0	12.0	0.76	7,000	7,700	218,000
90,000	120,000	298.0	285.0	46.0	11.8	0.76	6,200	6,800	177,000
80,000	100,000	280.0	268.8	43.4	11.4	0.73	6,000	6,500	140,000
52,000	58,000	247.3	231.0	34.8	9.5	0.74	4,150	4,600	75,000
27,000	40,000	207.8	196.0	29.3	9.2	0.74	2,900	3,300	40,000
LNG Carriers (Spheres, Moss)									
75,000	117,000	288.0	274.0	49.0	11.5	0.74	8,300	8,800	145,000
58,000	99,000	274.0	262.0	42.0	11.3	0.78	7,550	8,000	125,000
51,000	71,000	249.5	237.0	40.0	10.6	0.69	5,650	6,000	90,000
LPG Carriers									
60,000	95,000	265.0	245.0	42.2	13.5	0.66	5,600	6,200	
50,000	80,000	248.0	238.0	39.0	12.9	0.65	5,250	5,800	
40,000	65,000	240.0	230.0	35.2	12.3	0.64	4,600	5,100	
30,000	49,000	226.0	216.0	32.4	11.2	0.61	4,150	4,600	
20,000	33,000	207.0	197.0	26.8	10.6	0.58	3,500	3,900	
10,000	17,000	160.0	152.0	21.1	9.3	0.56	2,150	2,500	
5,000	8,800	134.0	126.0	16.0	8.1	0.53	1,500	1,700	
3,000	5,500	116.0	110.0	13.3	7.0	0.52	1,050	1,200	
Note: Dimensions given in the tables may vary up to ±10 % depending on construction and country of origin.									

Table 5.1: Typical dimensions of LNG and LPG tankers (from: Puertos del Estado, 2007).

The terminal concepts are similar to those of oil terminals: jetties or offshore buoy systems. Storage can be in special cryogenic tanks onshore, but also in in so-called Floating LNG Storage and Re-gasification Units (FSRUs), permanently moored vessels where tankers come alongside for unloading liquefied or loading re-gasified LNG (Figure 5.10).

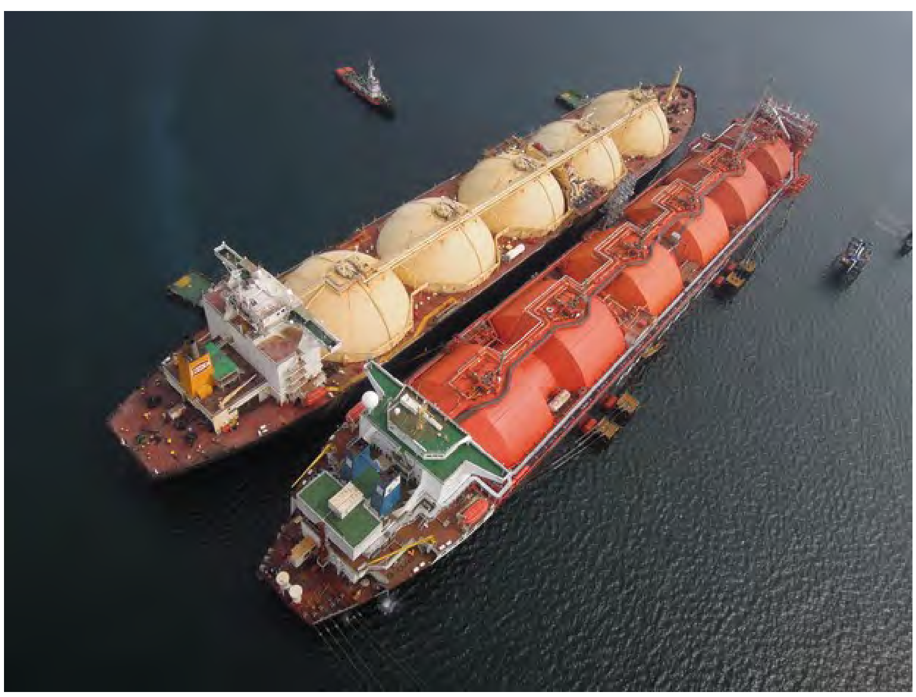


Figure 5.10: Offshore moored FSRU with an LNG-tanker alongside, West Java, Indonesia (Offshore LNG import terminal mooring in Indonesia by Royal HaskoningDHV is licenced under CC BY-NC-SA 4.0).

LNG and LPG terminals come with a risk of gas explosions. Ligteringen (2017) refers to a TNO study of the effects of a main LPG tank failure: “If a 28,000 m^3 tank of an LPG carrier is ruptured and ignites, a column of fire will develop with a diameter of 600 m and a height of 550 m for a duration of 6 min; first-degree burns will be sustained up to a distance of 2200 m. With delayed ignition, an explosion may occur (with LPG, but not with LNG) which, under unfavorable weather conditions, leads to a loss of 10% of the living quarters at a distance as far away as 7 to 11 km.”. Clearly, prevention by adequate precautionary measures is the only way to deal with this kind of extreme events.

Therefore, these types of terminals are often located at a place where the associated risk is acceptable. This requires a detailed study by safety experts, which usually leads to a map of risk contours (also see Part I – Section 2.2.5). Example box 5.1 describes the safety zones for a gas terminal.

Example box 5.1: Exclusion zones around a gas terminal

Non-Ignition Zone (NIZ) – area where non-essential people and vessel movements are not allowed, use of Personal Protective Equipment (PPE) is obligatory and ignition sources must be avoided or strictly controlled. The NIZ may be determined by national regulations and/or as part of a Quantitative Risk Assessment (QRA). A wide range of radii for Safety and Security Zones (SSZs) is found in literature, as a result of different company or national regulations.

Safety and Security Zone (SSZ) – area where only authorized vessels are allowed, specifically on business associated with the terminal, to avoid unnecessary risk in case of incidents at the terminal. The final SSZ size shall be determined with Hazard and Operability (HAZOP) and QRA during further terminal development.

Marine Zone (MZ) – this is the exclusion zone around the terminal where in principle no other ships should sail, with exception of vessels serving the terminal. If this is not possible, due to site limitations, this is the area where all passing vessels need to be closely monitored. The marine (exclusion) zone is established to minimise collision risks from sailing ships that need to pass the terminal. The final radius of the MZ will be determined with local Maritime Authorities, depending on the size of the vessels transiting and the speed allowed at the limit of the MZ.

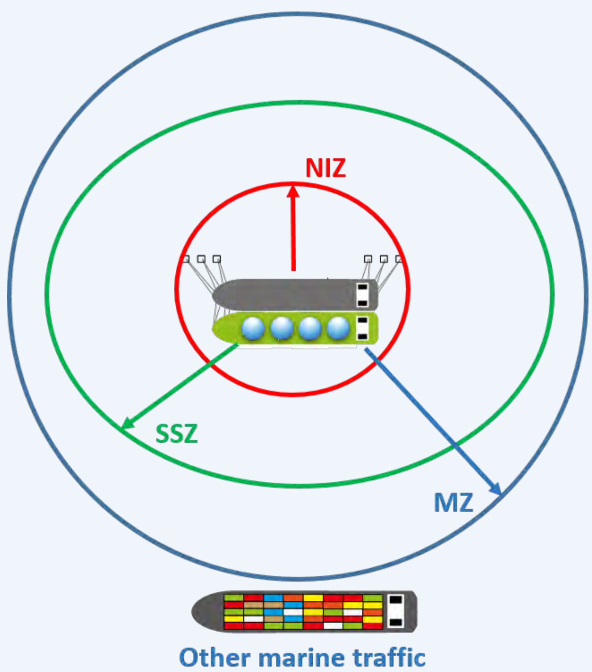


Figure 1. Safety zones for a gas terminal (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Example box 5.1 – continued on next page

Example box 5.1 – continued from previous page

For further reading see also:

- SIGTTO (1997) – “Site Selection and Design for LNG Ports and Jetties”
- PIANC (2012a) – PIANC Report N°116 “Safety Aspects Affecting the Berthing Operations of Tankers to Oil and Gas Terminals”
- PIANC (2016b) – PIANC Report N°153 “Recommendations for the design and assessment of marine Marine Oil and Petrochemical terminals”

Liquid chemicals are transported under various conditions of temperature and pressure, depending on the type. Figure 5.11 gives a summary for a number of often transported chemicals. In this figure the critical temperature is the temperature above which the material cannot be liquefied, no matter what pressure is applied. The diagram shows that ammonia, propane and butane can be transported at atmospheric temperature (Type 1 and Type 2 vessels), whereas methane, for instance, requires deep cooling, but can be transported under atmospheric pressure.

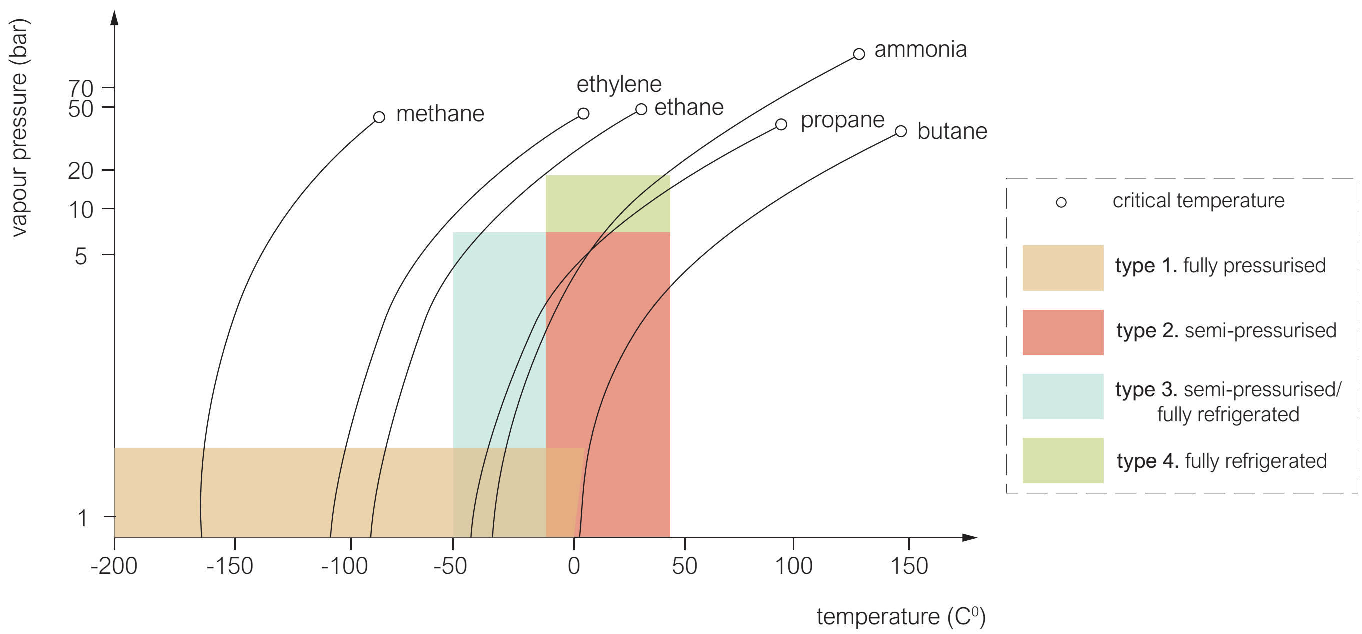


Figure 5.11: Transport conditions for different chemicals (reworked from Ligteringen, 2017, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The typology shown in Figure 5.11 is linked to the risk involved in the chemicals they transport:

- *Type 1* – for products with very serious environmental and safety hazards, requiring maximum preventive measures against leakage of cargo.
- *Type 2* – for products with appreciably severe environmental and safety hazards, requiring significant preventive measures against an escape of cargo.
- *Type 3* – for products with sufficiently severe environmental and safety hazards to require a moderate degree of containment, to increase survival capability in a damaged condition.

Most tankers are of Type 2 and 3, as highly hazardous chemicals are usually transported in small quantities.

5.1.3 Liquid chemicals terminal

Compared to the oil and the gas supply chains the liquid chemicals supply chain includes some additional elements, such as the production of the chemicals and the cleaning of the tanks after unloading (Figure 5.12). Tank degassing and cleaning is extremely important, because chemical gasses may involve health risks and the next cargo may consist of different chemicals.

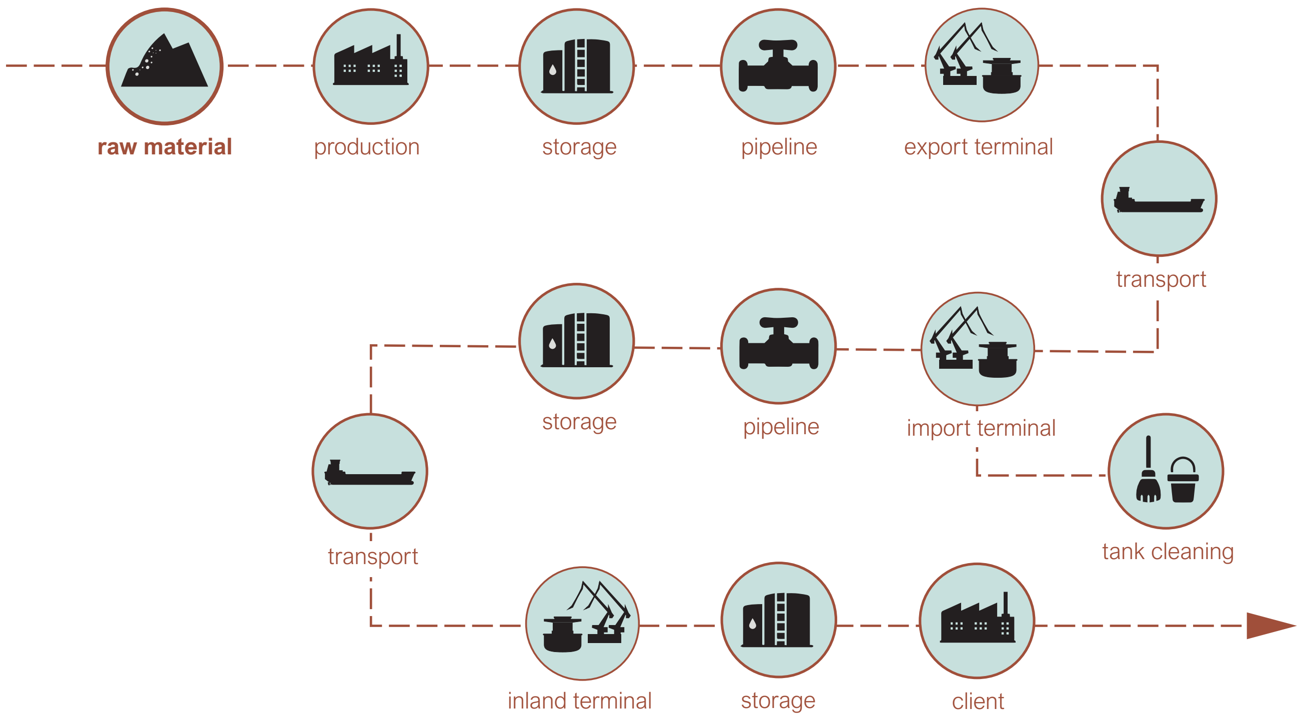


Figure 5.12: Schematic of the liquid chemicals supply chain (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The size of oceangoing chemical tankers ranges from 5,000 DWT to 35,000 DWT. They are smaller than other tankers, due to the nature of their cargo and the size restrictions imposed by the port terminals. They usually have several fully separated tanks, each with its own loading and unloading pipelines. Thus they can transport different types of chemicals during the same voyage and delver different chemicals at different ports during a roundtrip. Like in the case of container vessels on a roundtrip, this requires careful planning of port services.

Because of the emphasis on cleaning after unloading, the inside of the tanks on board of liquid gas carriers is kept as smooth as possible, in order to make them easier to clean with onboard tank cleaning machines. As a consequence, transverse stiffeners on deck must provide the vessel with sufficient stiffness (Figure 5.13). Before

Figure 5.13: Chemical tanker at sea; note the transverse stiffeners on deck (GULF OF ADEN (Dec. 13, 2007) by U.S. Navy photo by Cmdr. M. Junge is licenced under CC0 1.0).

being cleaned, the tanks must be degassed and ventilated, in order to be made free of explosive gases. In order to prevent explosions, filled as well as empty chemical cargo tanks are normally protected by a blanket of inert gas, often nitrogen.

The nature of liquid chemical cargo also puts special demands on the terminal equipment. The jetty needs additional pipelines for vapour return and scrubber systems for tanker cleaning. Hazardous gases need to be stored and treated. Storage tanks have to be double-walled, often with a concrete outer wall. As accidents may lead to dangerous gas clouds, exclusion zones have to be defined on the basis of a risk analysis. Blending may be needed before further transport to the hinterland. Some ports also offer laboratory services, in order to determine key specifications of the products handled (e.g. composition, purity, specific density, viscosity, pH).

For further reading see also:

- Ligteringen (2017) – "Ports and Terminals"

5.1.4 Hydrogen terminals

Hydrogen is expected to become an important carrier of clean and renewable energy and port authorities are already considering what role they wish to play in the hydrogen supply chain (Figure 5.14).

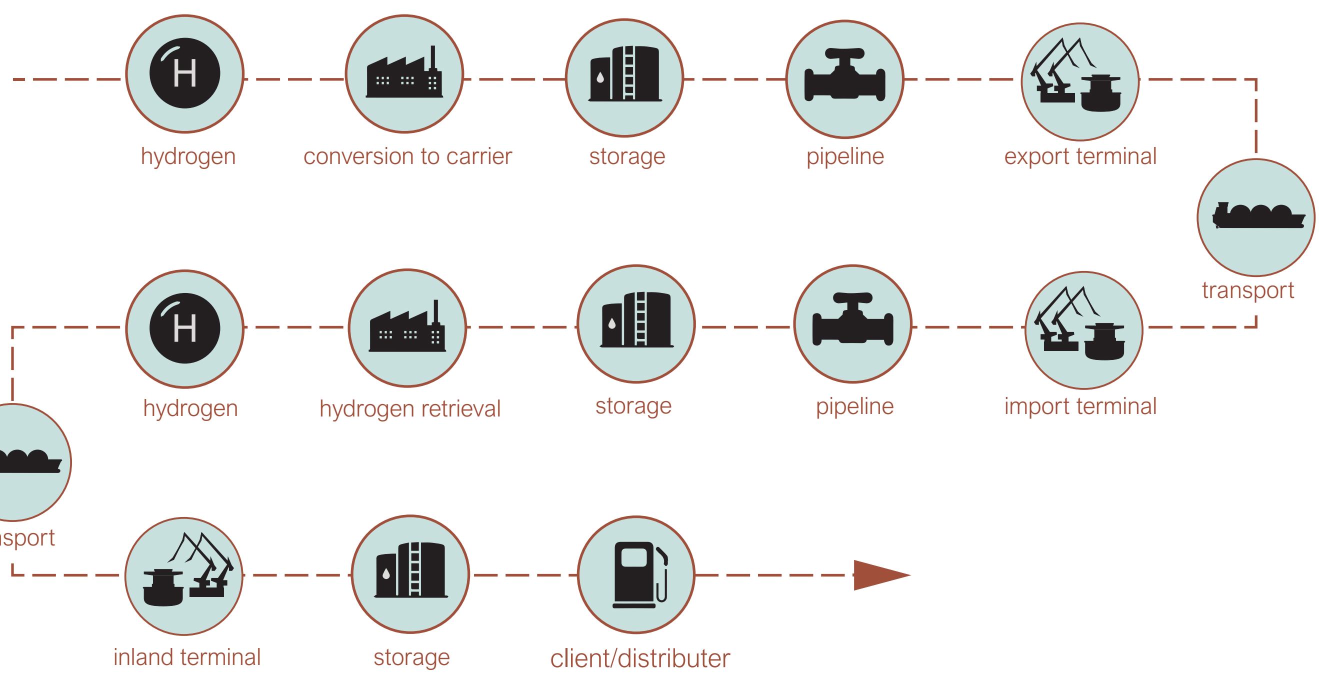


Figure 5.14: Schematic of a hydrogen supply chain (modified from Lanphen, 2019, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The hydrogen supply chain is somewhat more complex than the one of crude oil or liquefied gas. Hydrogen can be produced from different sources, among which fossil fuels and natural gas, but also from water (via electrolysis). At the moment, production from natural gas is the most cost-effective. This may change if the by-product CO_2 has to be captured and stored, or if CO_2 prices are raised.

Hydrogen can be stored and transported in different forms, called carriers (gaseous, liquefied, or chemically bound). Depending on the carrier and the location, long-distance transport can take place by ship or by pipeline. Because of the low density and the low boiling point under atmospheric conditions, gaseous hydrogen has to be stored and transported under high pressure. Liquefied hydrogen is stored and transported at a temperature of -253°C, but even then the density is relatively low (0.07 ton/m^3). Chemically bound hydrogen, e.g. in the form of ammonia (NH_3) or methylcyclohexane (MCH), can be stored and transported under less extreme conditions, but involves efficiency losses due to the chemical binding and retrieval processes.

The development of hydrogen supply chains is still in its infancy and common practice still has to settle. Figure 5.14

shows that many actors have to agree about the choices to be made. Although there may be power differences, none of these actors can decide on its own, they are all interdependent. For the port authorities of the exporting and the importing port, for instance, it makes a lot of difference in which form the hydrogen is transported. This determines important choices for the processing plant, for the terminal type (liquid or dry bulk), for the safety zones and for the facilities and the storage capacity at the terminal. They cannot independently optimise, however, on these investments and their timing: the plans and interests of the other parties involved have to be taken into account. This requires not only a good overview of what, where, when, who and how in the supply chain, but also a certain degree of coordination and collaboration.

The same goes for the vessels. Since the first hydrogen vessel has just been built (Figure 5.15), there are no vessel standards or classifications. This makes it difficult to design terminal facilities. Yet, rapid developments in this field are to be expected in the near future.

For further reading see also:

- Lanphen (2019) – "Hydrogen import terminal. Elaborating the supply chains of a hydrogen import terminal, and its corresponding investment decisions."

Figure 5.15: The world's first liquefied hydrogen carrier, the Suiso Frontier, launched December 2019 (© Kawasaki Heavy Industries).

5.2 Dry bulk terminals

5.2.1 Types of cargo

Dry bulk refers to cargo that is unpackaged and in granular, particulate form, as a mass of relatively small solids. For efficiency reasons it is generally transported in loose form and encompasses a wide range of commodities. Table 5.2 gives an overview of the evolution of dry bulk seaborne trade over the years 2013 - 2017.

Annual World Dry Bulk Seaborne Trade (Unit: Mtpa)						
Product	**Category**	**2013**	**2014**	**2015**	**2016**	**2017**
Major Bulk						
Iron Ore	Ore	1,189	1,338	1,363	1,410	1,478

Table 5.2 – Continued on next page

Table 5.2 – continued from previous page

Coal	Ore	1,184	1,218	1,144	1,410	1,193
Grain	Organic	392	432	495	480	505
	Total major bulk	2,765	2,988	2,966	3,030	3,176
Minor Bulk						
Agribulks	Organic	148	161	165	163	170
Sugar	Organic	56	54	56	62	59
Fertilisers	Processed product	143	154	155	150	162
Coke & Pet. Coke	Processed product	76	82	85	85	88
Bauxite	Ore	108	72	94	81	93
Alumina	Processed product	32	35	34	33	34
Manganese Ore	Ore	25	26	26	25	30
Anthracite Coa l	Ore	63	52	48	50	39
Cement	Processed product	104	108	103	110	109
Salt	Mineral	45	49	49	43	47
Nickel Ore	Ore	80	56	44	41	42
Copper Concentrate	Processed product	23	24	26	29	29
Scrap Iron	Processed product	106	104	101	101	110
Other	Various	121	125	128	131	140
	Total minor bulk	1,130	1,105	1,114	1,104	1,152
	Total all	3,895	4,093	4,080	4,134	4,328

Table 5.2: Seaborne bulk trade 2013 - 2017 (PIANC, 2019b).

Table 5.2 shows that dry bulk commodities can be categorised as:

- *major bulk* – such as iron ore, coal, grain, phosphate or bauxite, and
- *minor bulk* – such as sugar, rice, bentonite, gypsum, wood chips, salt or copra.

Before going into vessels and terminals, we first give a brief description of a number of major commodities, because their properties determine to a large extent the way they are handled and stored at the terminal.

Iron ore

Table 5.2 shows that iron ore is the most important dry bulk commodity, representing about one third of the total dry cargo shipment by weight. When shipped, the ore has a stowage factor between 0.30 and 0.52 m^3/ton, on average 0.4 m^3/ton. Sometimes the ore is concentrated and baked into small spheres or pellets.

Iron ore is generally dusty, so dust extraction is normally necessary. The density may be a limiting factor for stacking, because of the limited bearing capacity of the ground. The angle of repose is usually less than 40°.

Coal

Coal is the second most import dry bulk commodity. According to Table 5.2 it represents some 27% of the total dry cargo shipment by weight. The stowage factor of coal varies from 1.2 to 2 m^3/ton. The angle of repose varies between 30 and 45°.

Coal of all types may exhibit spontaneous combustion, as it absorbs oxygen when heated. The sensitivity, however, depends on the type. This sensitivity may limit the maximum allowable height of the stockpile. Dust nuisance can generally be controlled by water sprays, during unloading and transfer and when stored.

Grain

Different types of grain (wheat, barley, oats, rye, tapioca, quinoa, etc.) have different densities and properties, hence different storage and handling requirements. In the grain trade, variation in seasonal conditions results in large fluctuations in transport requirements. Various types of vessels of different sizes are used, including combined carriers. Some products, such as soybeans, are more and more containerised, in order to keep sight of the provenance.

Since grain is a perishable commodity, it is necessary to have proper ventilation and protection against weather conditions and pests during shipping and storage.

Phosphate

Phosphate rock is the main raw material for the fertiliser industry. It is very dusty and absorbs moisture rapidly, which can create problems for unloading. The average stowage factor is 0.92 – 1.0 m^3 per ton. Practically all shipments are in the form of a powdery concentrate. The material is very fine, and special provisions have to be made to prevent dust problems, including irritation and dust explosions.

Bauxite/alumina

Bauxite ore, when processed into alumina (Al_2O_3), is used as a raw material in aluminium industry. Bauxite and alumina differ significantly in bulk density: 0.80 to 0.88 m^3/ton for bauxite and 0.6 m^3/ton for alumina. There is a trend towards conversion of bauxite at the source, as this halves the transport load. Alumina in particular is dusty and requires precautions against inhalation, soil and air pollution.

As an illustration of the extent of worldwide trade in bulk goods, Figure 5.16 gives an overview of the global trade flows in some important agricultural products.

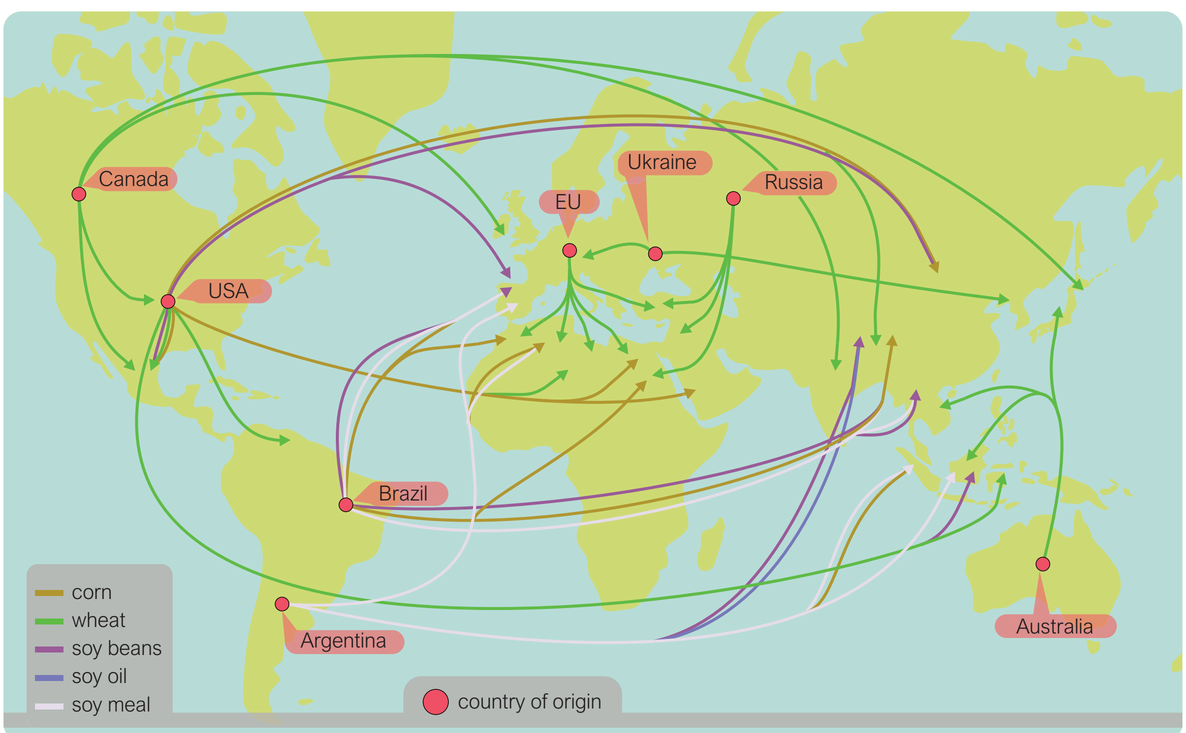


Figure 5.16: Global trade flows of some important agro-products (modified from https://www.bunge.com/our-businesses/managing-physical-flows by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

5.2.2 Types of vessels

Fleet and vessel sizes for dry bulk transport have grown over the years. In the past carriers have also been built for the transport of both dry and liquid bulk cargo. One example are the so-called Ore-Bulk-Oil (OBO) carriers, which were designed to carry both wet and dry cargoes. The idea of such combination carriers was to reduce the number of empty (ballast) voyages. Neither OBO, nor other types of combination carriers have been used at a large scale, and new ones are no longer built. In recent years the primary driver in vessel development was to achieve a greater economy of scale. The total fleet capacity, for example, has more than doubled between 2005 and 2015. Table 5.3 summarises present vessel characteristics.

Category	**Limiting factor**	**Maximum dimensions (m)**			**kDWT**
		L_s	B_s	D_s	
Chinamax	large port access	375	65	24	400
Valemax	large port access	375	65	24	400
Malaccamax	Strait Malacca	400	59	20	300
Suezmax	Suez Canal	300	50	20	200
Capesize	large port access	330	42	19	200
Newcastlemax	Port of Newcastle	300	47	17	185
Dunkirkmax	Port of Dunkirk	289	45	16	175
Neo-Panamax	Panama Canal (new)	366	49	15.2	120
Panamax	Panama Canal (old)	295	32.3	12	80
Kamsarmax	Port of Kamsar	229	32.2	14.4	70
Seawaymax	St. Lawrence Seaway locks	226	23	7.92	25.5
Handymax	small port access	175	28	11	55
Handysize	small port access	140	21	9	35

Table 5.3: Dry bulk vessel categories (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Like container and liquid bulk carriers, dry bulk carriers have been adapted to the navigability restrictions on the routes on which they operate or the ports at which they call. This has led to the classification shown in Table 5.3. Note that the Valemax (Figure 5.17) is a subcategory of the Chinamax, named after the Vale mine company in Brazil.

Figure 5.17: The Vale Sohar, a 400,000 DWT dry bulk carrier of the Valemax class (Vale Sohar in Nantong by Dmitriy Lakhtikov is licenced under CC BY-SA 3.0).

Bulk carriers can also be distinguished by the way they are unloaded. Like loading, unloading is commonly done with shore-based equipment, but for unloading also ship-based equipment can be used. In that case, there are so-called geared bulk carriers and self-unloaders. Geared carriers are equipped with deck-mounted grab cranes, generally one for every hold (Figure 5.18, left). Self-unloaders are equipped with a continuous unloading system consisting of horizontal and vertical conveyors (Figure 5.18, right; also see Youtube: How does a self unloader work?).

Figure 5.18: Dry bulk carriers with on-board unloading equipment; left: geared Handysize carrier (Polish Bulk Carrier Kociewie in the Port of Hamburg by Buonasera is licenced under CC BY-SA 3.0); right: self-unloader (CSL Trimnes by Cavernia is licenced under CC BY-SA 4.0).

5.2.3 Types of terminals

The berth configuration varies with the carrier type, but also between export and import terminals. Dry bulk terminals are seldom import and export terminal at the same time. In the next subsections we discuss several types of dry bulk terminals.

Export terminals

Export terminals are often dedicated to a single product, such as coal, ore or grain. Their location is generally close to the mine or the process plant. If direct loading is not feasible because a suitable port is too far away, the cargo may first be loaded into barges which bring it to deep water that can accommodate large carriers.

Loading is always done with shore-based equipment, either travelling along the ship, or serving the ship from a fixed point with a swaying arm. The latter requires less of a quay structure, but the loading equipment itself is more complex. In any case, the loading equipment must be able to reach each hold of the ship, but spreading the cargo over the hold is not necessary, gravity helping out. Figure 5.19 shows some examples of loading arrangements.

Figure 5.20 shows an example of a combined import and export jetty for iron ore in the deep-water port of Sohar, Oman. At import side (right at the photo), the world's largest ore carriers can be accommodated for unloading. At the export side (left at the photo), smaller transhipment vessels can be loaded, either with ore or with iron pellets produced at the terminal.

Import terminals

Most import terminals consist of linear single-sided berths with unloading machines of different types, either ship-mounted or land-based. Most commonly, they deliver the product to a terminal buffer stockpile, from where it is loaded into trucks, trains of inland vessels. PIANC (2019b) distinguishes three types of unloaders, as summarised in Figure 5.21. Figure 5.22 shows four examples of continuous unloaders.

These unloaders determine the requirements to the onshore part of the terminal. A gantry crane with a grab unloader, for instance, has to travel over a quay structure over the entire length of the moored vessel. A self-

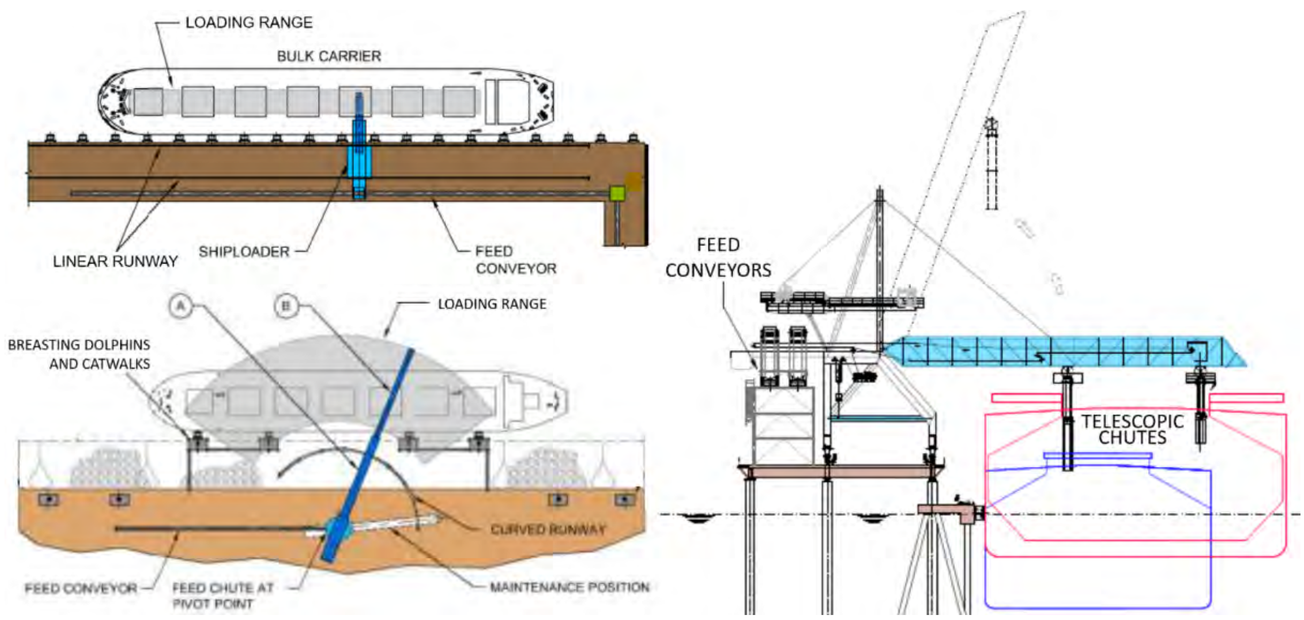


Figure 5.19: Examples of dry bulk loading equipment; top left: shuttle boom shiploader; bottom left: quadrant radial shiploader; right: long travelling shiploader (PIANC, 2019b).

Figure 5.20: Iron ore terminal, Port of Sohar, Oman (Bulk IJzerertsterminal in de haven van Sohar (Oman) by Royal HaskoningDHV is licenced under CC BY-NC-SA 4.0).

unloader, on the other hand, can do with a simple dolphin mooring, because it can deliver the cargo at a single point (Figure 5.23).

The capacity of the unloading equipment generally determines the terminal throughput capacity. The unloading capacity depends not only on the equipment, but also on the conditions (full hold, experienced operator, start of the shift) and the degree to which the hold has been unloaded (Figure 5.24). Therefore, different types of capacity are distinguished:

- Peak capacity (optimum circumstances, free digging); this should be the design capacity for all downstream equipment and plant facilities (conveyors, weighing equipment, stackers, stockage, et cetera).
- Nominal (rated) capacity, free digging rate under average conditions over an extended period.
- Effective capacity, average hourly rate for entire ship load, including trimming, cleaning, moving between holds, et cetera).

An unloading grab crane at the EMO-terminal in the Port of Rotterdam, for instance, has a grab volume of 45 ton and can make 100 cycles per hour. The corresponding capacities are:

- Peak capacity 4,200 ton/hr,
- Rated capacity 3,400 ton/hr, and
- Effective capacity 1,700 ton/hr.

As a first approximation, the capacity of a berth follows from:

$$C_b = p \cdot t_{\text{eff}} \cdot m_b \tag{5.2}$$

in which:

p	=	effective capacity of the (un)loading equipment,
t_{eff}	=	effective number of operational hours per year,
m_b	=	estimated berth occupancy rate.

A more detailed assessment of the required number of berths, unloading equipment and storage silo's and warehouses can be made by following the steps described in Section 3.3.3 (see Section 4.4 for their application to a container terminal). Queueing theory and simulation models can be applied to further study the extent to which the design meets throughput requirements and waiting time limitations.

A special point of attention is hold cleaning after unloading. Hold cleaning, which is necessary to prevent cargo contamination, corrosion, et cetera, is strictly overseen. A vessel may even be held in port if it does not comply with the hold cleaning rules. If the cleaning takes place while the vessel is at berth, this will reduce the berth capacity.

The overall terminal layout varies between cargo types: requirements to stocking iron ore or coal are different from those to stocking grain or sugar (Figure 5.25). PIANC (2019b) gives a number of examples of terminal designs.

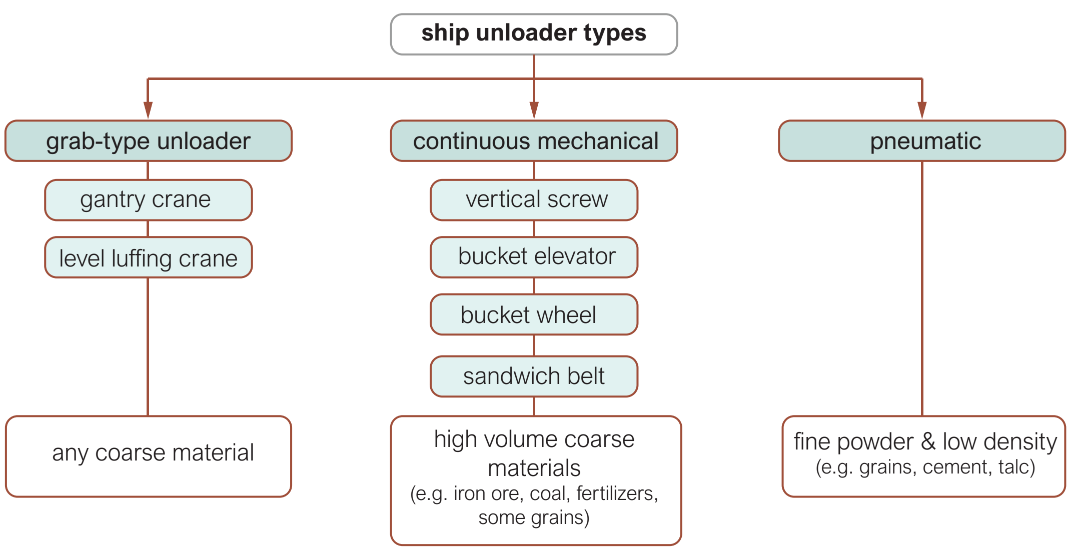


Figure 5.21: Ship unloader types (reworked from PIANC, 2019b, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 5.22: Continuous unloaders; top left: bucket elevator type; top right: chain type; bottom left: pneumatic type; bottom right: screw type (images by PIANC, 2019b, are licensed under CC BY-NC-SA 4.0, Port-de-commerce-de-Lorient by Pline is licenced under CC BY SA 3.0).

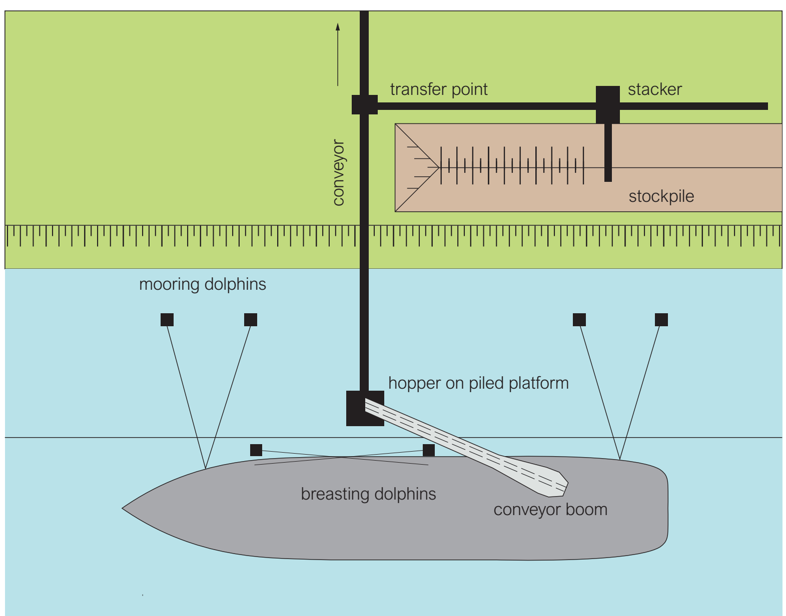


Figure 5.23: Self-unloading arrangement (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

5.2.4 Transhipment terminals

Although most dry bulk terminals are either import or export terminals, there are also transhipment terminals for further transport by short sea shipping and/or IWT. One example is the EMO-terminal for coal and iron ore

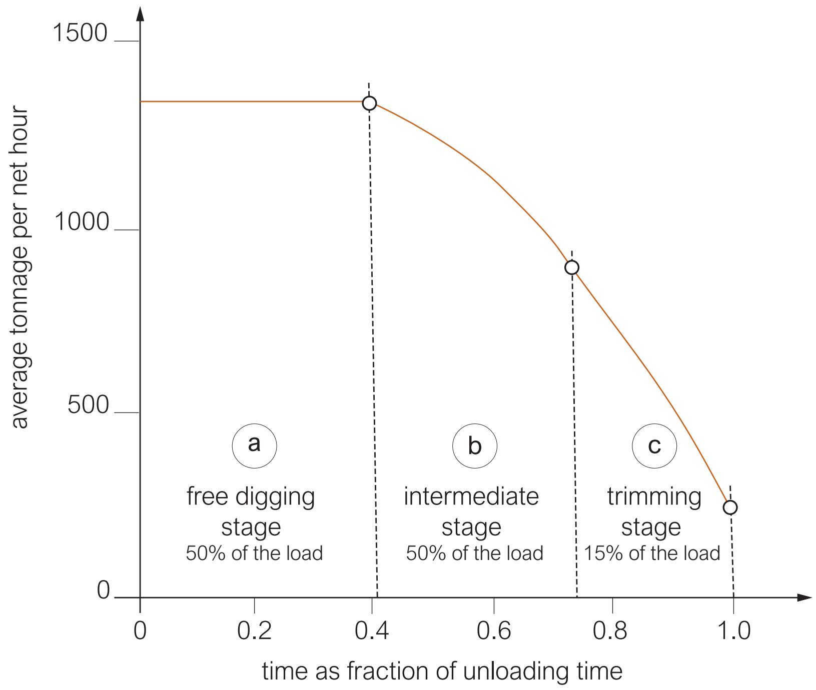


Figure 5.24: Unloading capacity as a function of time (reworked from Ligteringen, 2017, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

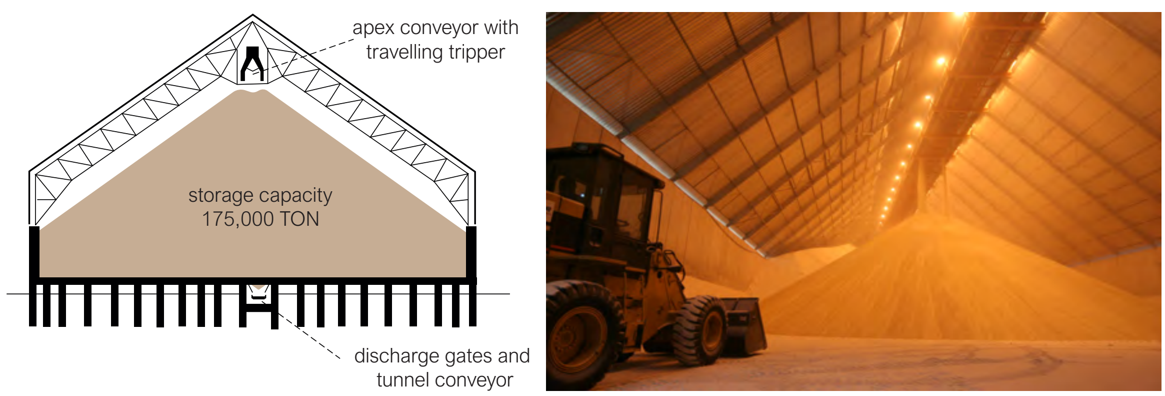


Figure 5.25: Stacking, storage and reclaiming of sugar (left: image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0, right: Terminal Graneleiro em Operacao - Sugar Mill Santos Harbor by Sabino Freitas Correa is licenced under CC BY-SA 4.0).

(throughput 40 mio ton/yr) in the Port of Rotterdam (Figure 5.26). This terminal has separate quays for large carriers, short sea vessels and IWT barges.

If a port is not accessible to large ocean-going carriers, the cargo is sometimes reloaded into smaller ships at a deep-water offshore terminal (Figure 5.27). Another way of dealing with a too shallow access is to unload part of the cargo onto smaller vessels. This is done, for instance, with bulk carriers on the Western Scheldt, on their way to the Port of Antwerp.

For further reading see also:

- PIANC (2019b) – PIANC Report N°184 “Design principles for dry bulk marine terminals”

5.3 Cruise terminals

Cruise shipping is a rapidly growing branch of the port and shipping industry. This applies to ocean-going as well as inland cruising. Ports adapt to this trend by increasing their cruise terminal capacity. On the other hand, this

Figure 5.26: EMO-terminal for coal and iron ore, Rotterdam (PIANC, 2019b): (1) large carrier unloading quay; (2) short sea vessel loading quay; (3) barge loading quay.

Figure 5.27: Offshore salt terminal, Porto-Ilha de Areia Branca, Brazil (Salt ship loading by Marcus Guimares is licenced under CC BY 2.0).

market is rather volatile, as has become clear during the 2020 Corona pandemic (Figure 5.28).

Figure 5.29 outlines the 'supply chain' of the cruise shipping industry. Clearly, cruise terminals differ from container, liquid and dry bulk terminals.

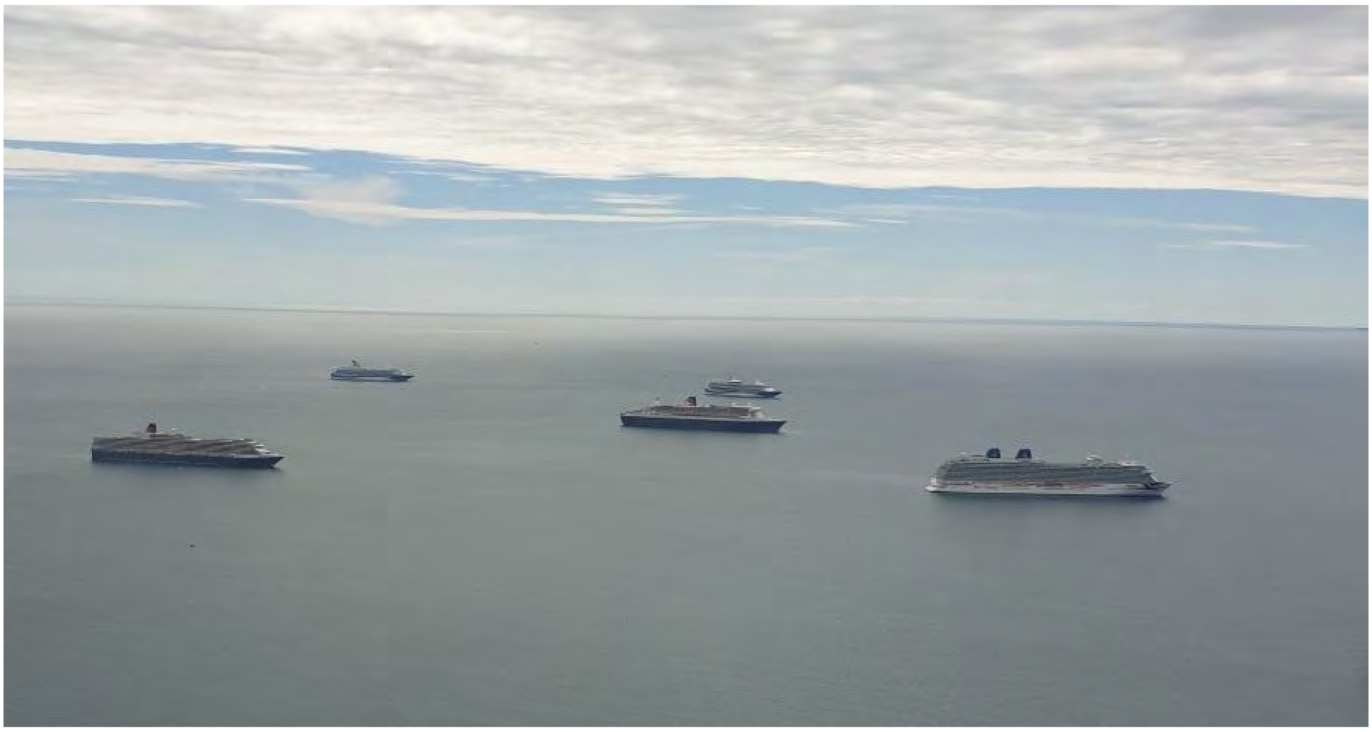


Figure 5.28: Large cruise ships waiting for business off the Weymouth Bay (UK), summer 2020 (Cruise Ships from the Air by Andrew Bone is licenced under CC BY 2.0).

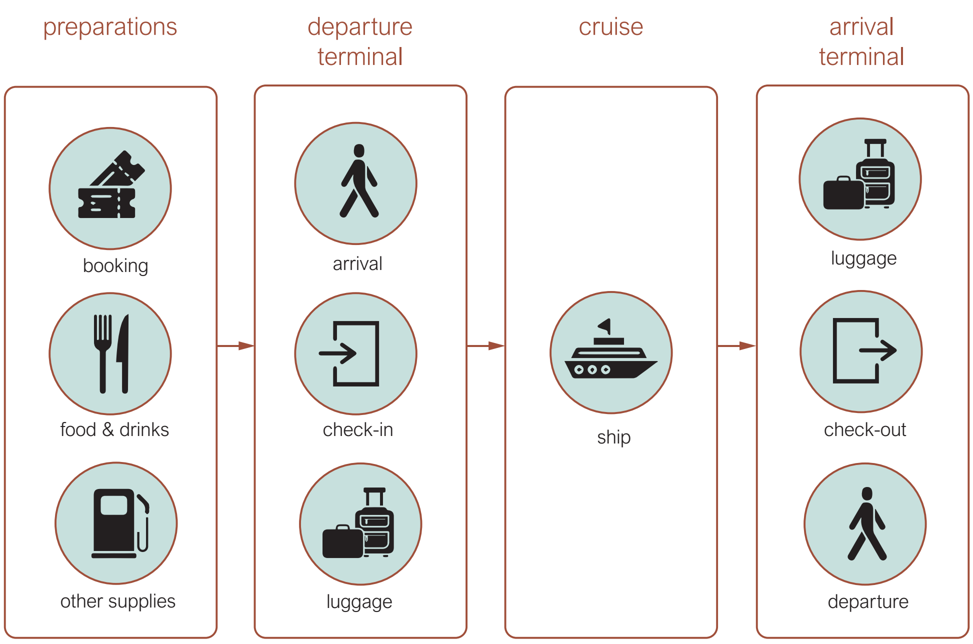


Figure 5.29: Schematic of the cruise shipping process (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Along with the increasing demand, cruise vessels have increased in size. At the moment, the largest ones are not much smaller than other large ships (Figure 5.30, left). The largest cruise ship at the moment is the Symphony of the Sea, measuring 360 x 65.7 x 9.32 m, with a gross tonnage of 228,081 and accommodating up to 6,680 passengers.

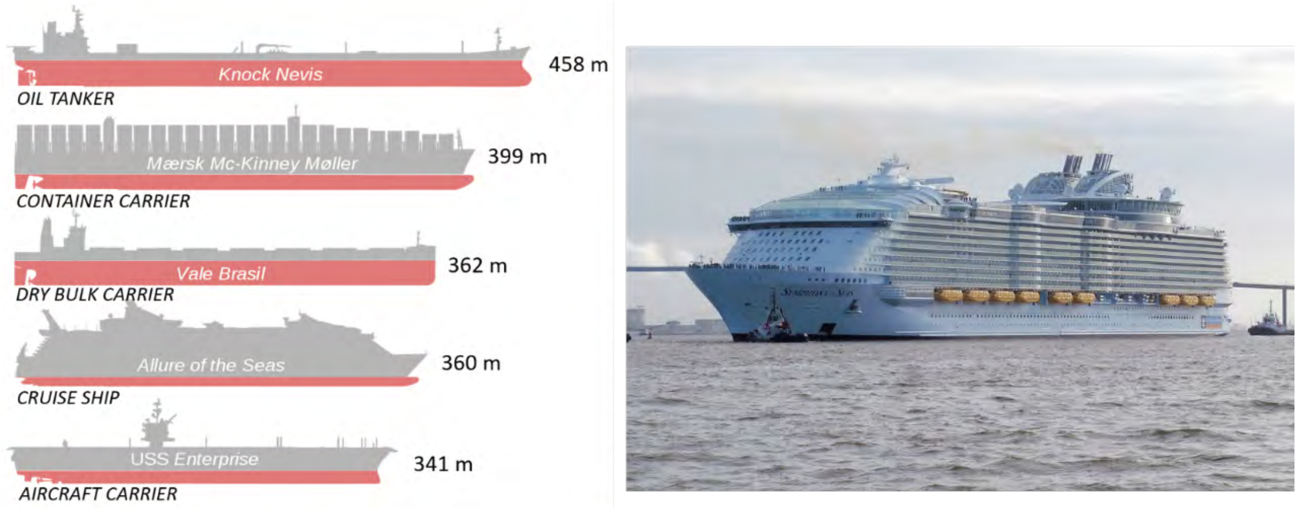


Figure 5.30: Ocean-going cruise ships, no longer much smaller than other ships; left: the world's longest ships (Bateaux comparaison2 with Allure by Delphine Ménard and Tupsumato is licenced under CC BY-SA 2.0); right: the Symphony of the Sea (SymphonyOfTheSeas by Darthvadrouw is licenced under CC BY-SA 4.0).

Apart from a terminal building for passenger handling, a cruise terminal generally provides long-duration parking space and facilities to accommodate passengers while waiting, such as a restaurant. Sometimes the terminal buildings include facilities for other activities, such as meetings and conferences. The Cruise Terminal Rotterdam, for instance, has a famous restaurant, a congress centre, meeting rooms, a dancing hall and a fair and exposition hall.

River cruise ships also tend to grow ever larger. The biggest ones at the moment are 135 m long and can accommodate more than 200 passengers (Figure 5.31). River cruise terminals are generally less extensive than the ones for ocean-going cruise ships, but the bigger ones still offer a range of facilities, such as a parking, shops, a restaurant and a tourist information office.

Figure 5.31: The A-Rosa-Aqua, one of the largest river cruise ships. (A-Rosa Aqua (ship, 2009) by Rolf Heinrich, Köln is licenced under CC BY-SA 3.0).

For further reading see also:

- PIANC (2016c) – PIANC Report N°152 "Guidelines for Cruise Terminals"
- Ligteringen (2017) – "Ports and Terminals"

5.4 Other port and terminal types

In terms of cargo volume the most important terminal types are: container terminals (Chapter 4), liquid bulk terminals (Section 5.1) and dry bulk terminals (Section 5.2). A brief description of cruise terminals was given in the previous section as an illustration of how its process differs significantly from the other terminal types. Obviously there is a range of other terminal types that we have not yet discussed:

- *Ro-Ro terminals* – Roll-on/Roll-off terminals are designed to handle wheeled cargo that is driven on and off the ship on their own wheels (i.e. cars, trucks, semi-trailer trucks, trailers) or using a platform vehicle (i.e. a self-propelled modular transporter). This is in contrast to Lift-on/Lift-off (LoLo) vessels, which use a crane to load and unload cargo. The Ro-Ro terminals need facilities to accommodate the (un)loading ramps of the vessels, and generally large amounts of parking space. As such, designing a Ro-Ro terminal requires similar considerations when it comes to the number of terminal elements that are needed for a target capacity, and their order-of-magnitude dimensions.
- *General cargo or break bulk terminals* – Break bulk differs from containers and (liquid and dry) bulk in the sense that the cargo are goods that must be loaded individually. An important distinction with containers is that break bulk does not have standardised dimensions to facilitate (un)loading and storage. Break bulk cargo is, for example, transported in bags, boxes, crates, drums, barrels and packed pallets. One of the challenges of designing a general cargo terminal is making sure that the terminal is flexible in handling and safely storing the potentially large variety of goods. Other than that, similar challenges are faced when it comes to making cargo forecasts, estimating the fleet composition and deriving the required number of terminal elements and their order-of-magnitude dimensions to meet the forecasted demand.
- *Fisheries ports* – Fishing ports are designed for landing, temporarily storing and distributing fish. This may take place in a recreational facility, but is usually commercial. The type of fisheries that the port caters to affects its layout. A fisheries port that caters to vessels that fish locally (days), needs different facilities than a port that caters to vessels that fish remote grounds (days – weeks). Not only are the dimensions of the vessels quite different in both cases, also the amount of fish that is potentially brought in per arrival. Again the design challenge is to estimate the terminal elements required to handle the projected payload. But also ensuring proper connections to markets is key. The balance between access to fishing grounds and access to markets was one of the core issues of the 2020 Brexit negotiations.
- *Marinas* – A marina typically caters to yachts and small boats. Security and on-site facilities like, parking spaces, toilets, showers, electricity, running water, small shops, restaurants, etc., can make a marina more attractive. But in some cases also access to, and attractiveness of, the region around the marina can be a factor of attraction. Typical design challenges are of course to arrange optimal facilities on the available scarce area. Again the expected vessel mix the marina should cater for is influential. The expected client will have a great influence on the service levels that need to be provided. Furthermore, making sure that the marina design is such that customers can safely enter/leave the marina, and conditions while moored are as comfortable as possible, is important.

The above bullet list only lists a number of aspects that are important for a small selection of port and terminal types. Obviously there is much more to consider for the ports and terminals mentioned. Also the list of port and terminal types could have been much longer. Detailing aspects associated with each port and terminal type is outside the scope of this book. For more information on ports and terminals the reader is referred to Ligteringen (2017).

5.5 Inland ports

A type of port that we do consider to be in scope for more detailed discussion in this book is the inland port or harbour. Inland ports play an important role in the supply chain as transfer points in the hinterland distribution of cargo; exporting from a production site or importing towards the end users, with the 'last mile' often covered by trucks or rail. This section discusses the IWT-terminals at inland ports and along river or canal banks, but it also pays attention to facilities required in overnight harbours.

5.5.1 Typology and change

Inland ports range from sophisticated multiple-basin complexes with up-to-date handling equipment, to simple one-berth terminals along the bank of a river or canal for incidental loading or unloading of goods or passengers. The city of Nijmegen, situated on the Waal, in the Netherlands, provides examples of this diversity within a stretch of 4 km (see Figure 5.32). From East to West we see the (a) Lindenberghaven, (b) the Waalhaven and (c) the Oostkanaalhaven.

The Lindenberghaven, which is a marina (port for pleasure crafts), is situated *on* the river Waal. It is positioned in the outer bend, and the marina opening is facing down stream. The quay directly bordering it to the west, the Waalkade, marks the edge of a location known as the 'old harbour' (in Dutch: 'Oude haven'). This was the location of the city's port for centuries, up to the 1850s when the city authorities decided to fill in the harbour basins and construct a new harbour outside the city walls. An important reason for this was to prevent the inner city from being flooded by the River Waal. The Waalkade is nowadays mainly used for recreational purposes.

The Waalhaven is the 'new harbour' that was constructed following the decision to fill in the 'old harbour' in the 1850's. It is positioned *next to* the river Waal, with an open connection and placed right next to the rail network. From the 1850's up to the 1990's this was the industrial port of Nijmegen. Due to space limitations additional port space was developed, starting in the 1950's, a bit further west at the position of the current Oostkanaalhaven. Since the 1990's all industrial activities moved from the 'new harbour' to the Oostkanaalhaven. Eversince the 'new harbour' is mainly used as an overnight harbour for IWT vessels.

The Oostkanaalhaven is an example of a modern multi-basin industrial port. Its two main water areas were constructed in the 1950's. It is well connected to the wider IWT network through its positioning on the Maas-Waal canal. The connection to the Waal is via a lock, preventing changing water levels in the Waal to affect the port operations directly. The port is furthermore well-connected to the wider road network and situated closely to rail connections.

The ports in the city of Nijmegen provide a nice example of the diversity of inland ports, but their evolution over time is also an example of the trend to move port facilities away from city centres more to the fringe where more space is available (see also Figure 2.1). Another driver for this trend has been the growth in ship size.

5.5.2 Challenges of inland port planning

As indicated in Part I – Chapter 2, ports need to adapt to never ending triggers of change. This is true for sea ports but also for inland ports. The Nijmegen example already illustrates how ports need to move to grow, among others in response to changes in society. But other triggers of change also apply.

Economic and political changes can have consequences as well. One example is the history of the Twente kanalen in the East of the Netherlands: triggered by Belgian independence in 1830 and the opportunities provided by the industrial revolution, the textile industry in the region of Twente developed spectacularly during the second half of the 19^{th} century. The population of Enschede, for example, multiplied by a factor five in the period between 1870 and 1900. To stimulate the supply of cotton, and coal from the mines in the South of the Netherlands, a canal network was constructed in the 1930s to connect Almelo, Hengelo and Enschede to the IJssel and the further IWT-network. This stimulated the textile industry to grow even further. But several economic and political changes triggered a dramatic decline from the 1960s onwards: economic developments caused the prices of textile products to drop (i.e. overproduction, changing markets), workers wanted to earn higher wages causing labour shortages and further erosion of competitiveness, the discovery of natural gas in North of the Netherlands led to the political decision to close the mines in the South, et cetera. All these developments together caused the textile industry, which employed approximately 43,000 people in the mid 1960s, to collapse to approximately 8,700 employees in the 1990s. All this of course had its impact on cargo flows and associated port activity. Nowadays the main cargo in the port of Hengelo is salt, which is still mined in the region in ground layers between 300 and 3,000 m down.

Also extreme conditions can have a significant effect on the IWT transport mode and inland ports. An episode of extremely low discharge on the River Rhine in 2018 caused water levels to drop significantly below the Agreed Low Waterlevel (ALW) for navigation during several months. Consequently, vessels needed to limit their load to lessen their draught (see: Van Dorsser et al., 2020). This caused transport costs of the IWT mode to rise, while road

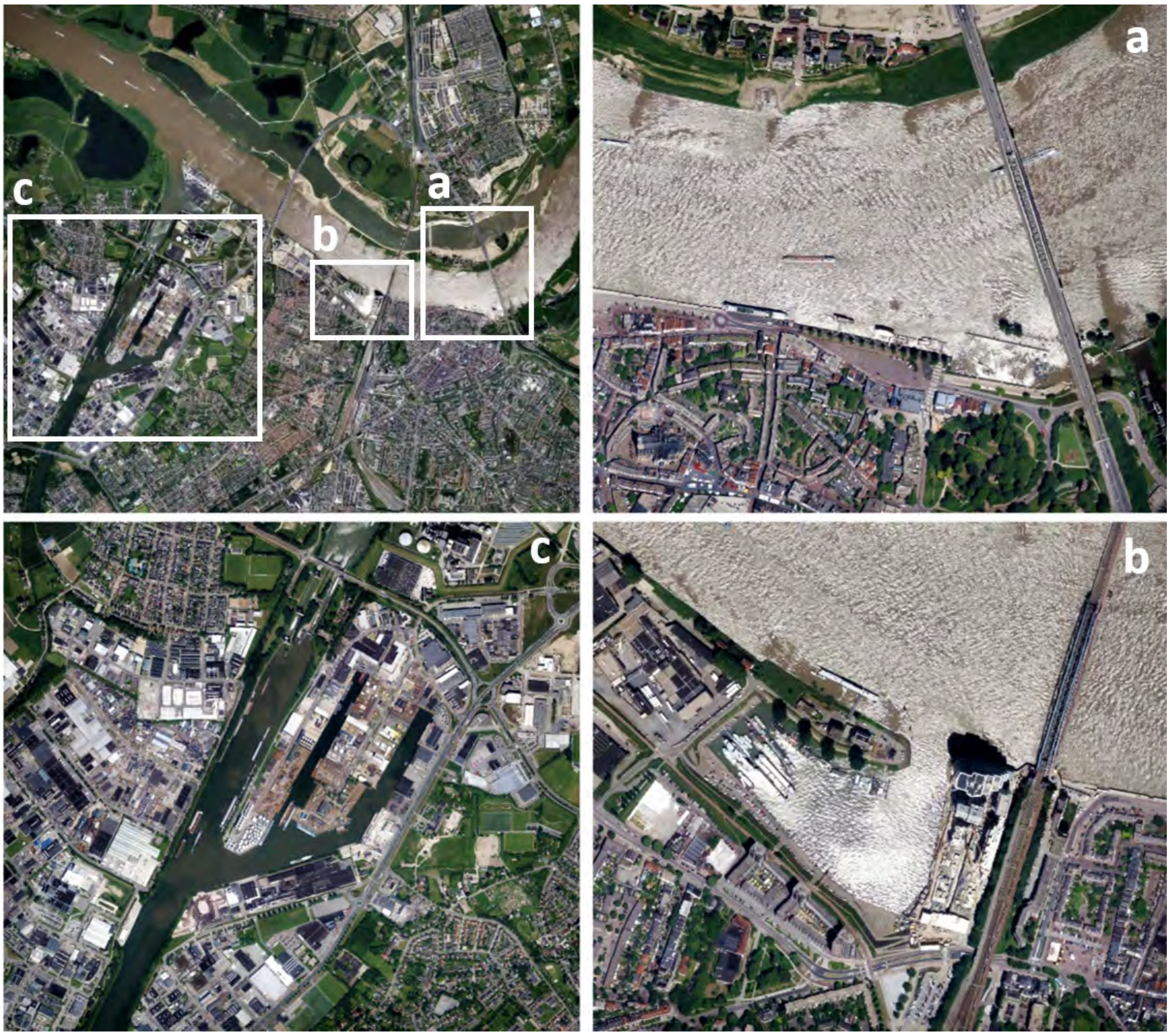


Figure 5.32: Variety of inland ports in the city of Nijmegen, the Netherlands, (a) the Lindenberghaven, (b) the Waalhaven, and (c) the Oostkanaalhaven (aerial imagery by the National Georegister (NGR) is licenced under CC BY 4.0).

and rail transport remained largely unaffected. At the most extreme discharge lows, several ports even became inaccessible. If climate change causes such droughts to occur more frequently, this constitutes not only a challenge for the inland port infrastructure, but it also raises concerns about a modal shift away from IWT.

Besides threats there are also opportunities. In the upcoming energy transition IWT has the potential to have a smaller environmental footprint than other transport modes. Whereas road networks tend to become more congested, IWT-networks still have room for growth. Furthermore, the steady increase of container transport creates opportunities for the further development of inland container ports.

The above examples are meant to underline uncertainties that IWT and inland ports need to deal with. Careful planning under conditions of uncertainty is of vital importance, and the paradigm of Adaptive Port Planning applies. The steps described in Chapter 2 are used for inland port planning as well. A Port Master Plan is needed and any decision should be based on a careful estimate of future cargo flows and vessels that the port should be able to handle. For a greenfield inland port site selection is crucial: it requires a delicate mix between access to various transport networks (road, rail, IWT, pipeline) and proximity to production locations and/or end users. Once future demands are estimated and the anticipated vessel mix is defined, a port layout can be developed; conceptual at first, more detailed later on.

5.5.3 Inland port layout

Preceding any port layout effort, location selection is one of the most important outcomes of the port planning process. Apart from economical and logistical considerations, which are obviously very important from a feasibility perspective, a number of civil engineering aspects is essential as well:

- Inland ports are preferably located at the outer bend of a river, where the water depth is the largest. Part III – Section 2.4 shows examples of different types of ports: open ports, ports closed off with a lock from the river, etc.
- Quays located along a river bank may experience high current velocities. A berth should preferably be located at deep water and in line with currents, but at such locations the current velocities can be high. A small inclination (>5°) of a moored vessel's axis with respect to the current direction may already lead to high mooring forces.
- Rivers may carry high sediment loads, which can give rise to access channel blockage or basin sedimentation. This may even jeopardise the feasibility of the port. As river morphology can be complex and very dynamic, a port should be located on a morphologically stable part of the river. Maintenance dredging in very dynamic rivers may not be economically feasible for small ports.
- River ports should be sufficiently protected from floods, for instance by placing them on a landfill. If this sticks out into the river bed, however, it may negatively influence the river's flood conveyance capacity.

Part III – Section 2.4 gives more detailed guidelines for the dimensioning of water areas in inland ports. They concern, for instance, the width of the access channel entrance and the dimensions of turning basins and port water bodies, but also the preferred berthing arrangements.

Here we will focus on ports and terminals in commercial inland ports or at quays (terminals along river or canal banks), among which we can distinguish:

- *general-purpose ports* – multi-user interfaces between IWT and other modes of transport (road, rail), generally offering storage facilities; see for example Figure 5.32c and Part III – Figure 2.55;
- *dedicated ports* – for containers or other cargo, sometimes multi-user, sometimes single-user; see for example Figure 5.33 – left, but also Part I – Figure 1.21;
- *industrial ports* – they are generally the end of the transport line, where raw materials and (half-)finished products reach their final destination and end-products are loaded directly from the factory; see for example Figure 5.33 – right.

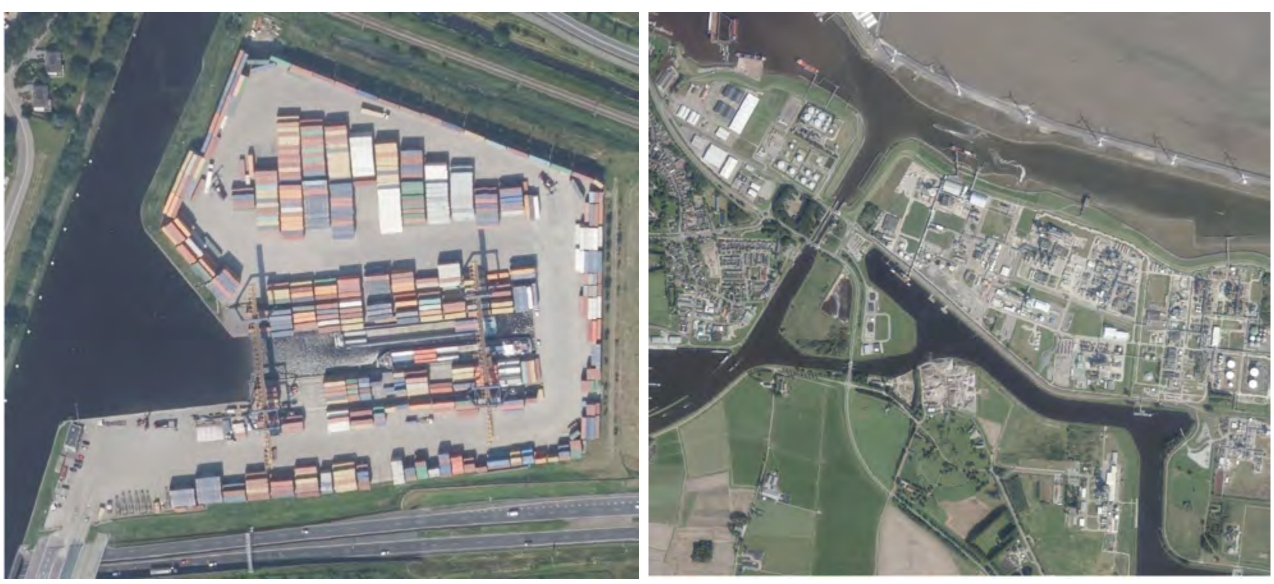


Figure 5.33: Left: dedicated container terminal on the Gouwe canal, Alphen aan den Rijn, exporting mainly Heineken beer via barge to Rotterdam and Antwerp; right: chemical industry terminal Delfzijl, connected to sea via the river Eems and to the hinterland via the Eemskanaal (aerial imagery by the National Georegister (NGR) is licenced under CC BY 4.0).

Compared with sea ports the available space on which the different inland port functions can be planned is generally much more limited. Furthermore since inland ports are often located in or near cities, and bordering along existing rivers or canal networks, the space that *is* available is often not ideally shaped, with odd angles and curves (see for example Figure 5.33). Despite these complications the development of a port layout at master plan level is quite similar to sea ports (see Section 3.2).

5.5.4 Inland port terminals

Terminal services and components

Like in the case of seaports, services provided in inland ports will differ per commodity. In general the following facilities will be available:

- mooring facilities,
- quay side cargo transfer equipment and terminal transport equipment,
- storage facilities,
- interfaces to other modalities (road, rail, and
- terminal support services (shore power, offices, workshops, security, etc.)

Mooring facilities

In ports with a more or less constant water level, such as canal ports or closed river ports with a ship lock (see Part III – Section 2.4), vessels can be moored along quays. In open river ports, however, the water level may vary too much for a fixed quay, so there one has to find another solution, such as a movable jetty with a floating pontoon (Figure 5.34).

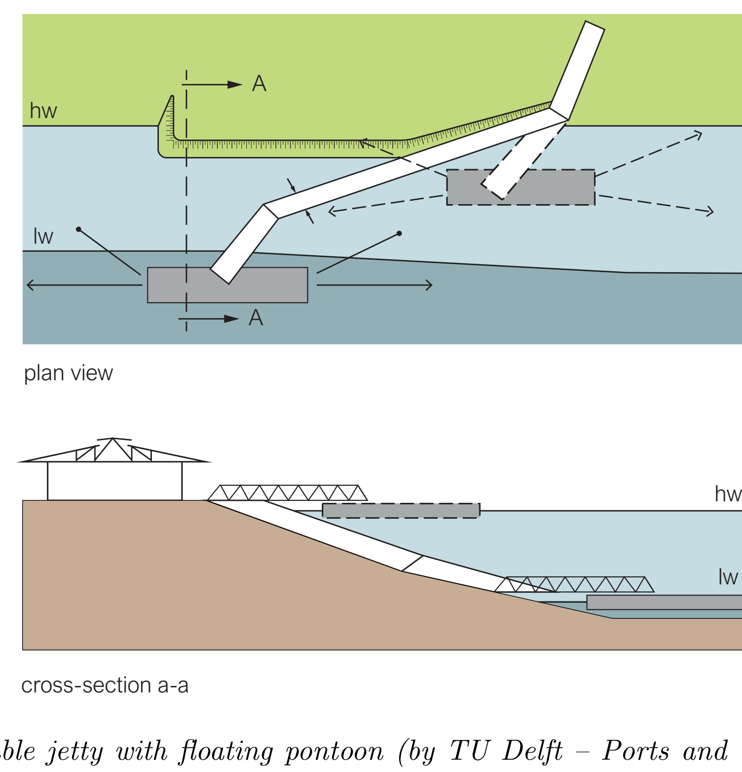


Figure 5.34: Layout movable jetty with floating pontoon (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Whatever the form (quay wall, fixed jetty, floating jetty), a berth must withstand the forces exerted on it (Figure 5.35). These forces may fluctuate considerably and vary from one location to another, so a thorough analysis is needed. Particular attention should be given to sudden changes of the water pressure caused by passing ships.

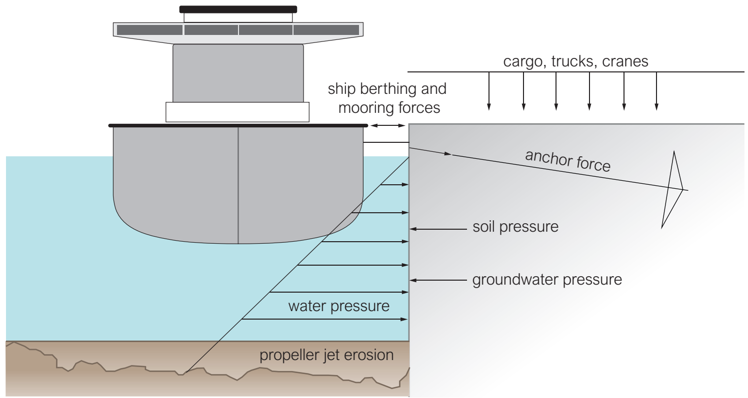


Figure 5.35: Forces acting on a quay wall (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Ship impacts may be considerable, e.g. in case of a failing manoeuvre leading to significant kinetic energy to be absorbed (see Part III – Chapter 5). The extent to which rough berthing manoeuvres are taken into account in the analysis is subjective. In that respect there is a difference between rigid structures and structures with a flexible fendering. In the latter case, the impact load will be smaller. RVW (2020) presents guidelines for the rope forces that can be expected at bollards as a function of the ship class.

Near a berth, ships will often be manoeuvring. Consequently, the risk of erosion due to propeller or bowthruster induced jets is relatively high, and should be given due attention. To prevent stability problems, sheet piles should be given some extra length, or a bed protection should be considered. Repair of structures and revetments in this kind of situations is generally rather costly. In Part III – Section 4.3 we present some first ideas. More details can be found in PIANC-report 180 (PIANC, 2015). For a further discussion of design aspects and relevant guidelines on quay wall design, we refer to EAU 2012 (Cywiński and Grabe, 2005).

Quayside cargo transfer equipment

The type of cargo determines the port equipment: cranes, overhead ropeway systems, cable-suspended drag buckets, various types of grab or continuous barge unloaders, et cetera. Figure 5.36 gives a number of examples, but many more exist.

IWT container terminals require one or more container cranes with a lifting capacity of about 40 ton. Since the beam of IWT vessels or barges is much smaller than that of sea-going container ships, the crane's outreach from the quay edge can be less. As the trolley and hoisting speeds are usually lower, as well, the investment in container handling equipment is significantly less than in a seaport, though still substantial in IWT terms.

In developing countries, (un)loading of barges is sometimes still done manually. In most cases, however, some form of mechanisation, or partial mechanisation, has been introduced. From an engineering point of view, mechanisation of cargo handling makes a considerable difference for the design of a terminal and, especially, for the design of the jetty.

Storage

Compared to seaports, inland ports generally have to cope with less space. As a consequence, rather than having large container stacks that are optimised for efficiency, storage arrangements are designed to make optimum use of the space available.

Clearly, required storage facilities depend on the type of cargo: tanks for liquid bulk, for instance, or closed storage sheds for dry bulk (agri products, minerals, iron ore). Containers are generally stored at the terminal and can serve as a sound wall (see Figure 5.33). Like in sea ports, an efficient system for managing the storage is required,

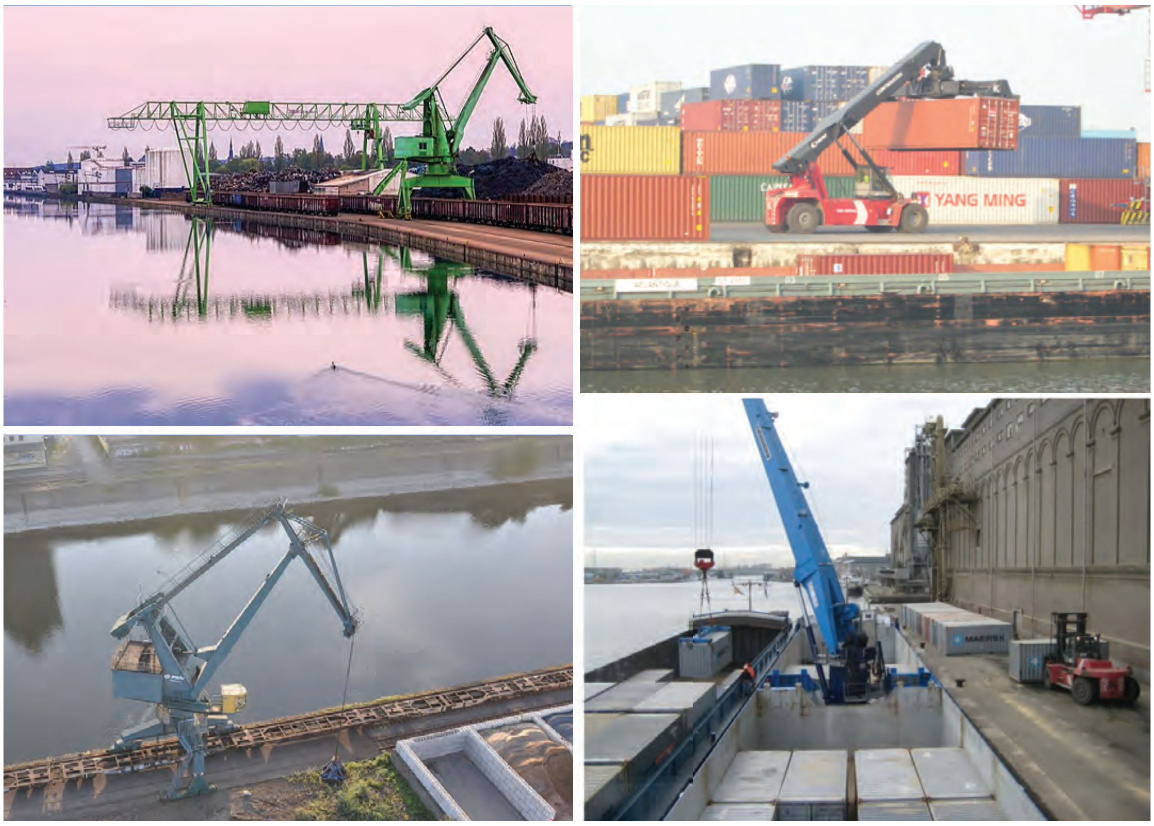


Figure 5.36: Examples of (un)loading facilities; upper left: gantry crane by Jürgen Striewski is licenced under CC BY-SA 4.0, upper right: reach stacker by Lundeux is licenced under CC BY-SA 2.5, lower left: quay mounted crane by Atamari is licenced under CC BY-SA 3.0, lower right: vessel mounted crane (from www.slideshare.net, "Crane Barges", Copyright by Mercurius Shipping Group).

though the different optimisation criteria may lead to different choices.

Interfaces with other modalities

Because of the space restrictions, transfer of cargo from storage facilities (tanks, sheds, container stacks) to rail or truck or vice versa requires special attention when developing the layout of an inland port. Gates for further transport of containers by truck can be used in combination with an Automatic Equipment Identification System (AEIS). Trucks or other terminal transport facilities are also necessary to transfer containers to rail. In case of dry or liquid bulk a system measuring the quantities entering or leaving the terminal to truck, rail or pipeline should also be available.

5.5.5 Facilities in overnight stay harbours

To enable crews to have rest periods, overnight stay harbours should be situated at regular distances along the waterway. Depending on the duration, the facilities will differ: just a safe mooring at a mooring pile for one night without disembarkation, or a mooring along a disembarkation facility, for example via a floating or fixed landing stage (Figure 5.37).

A growing number of vessels have spuds (cf. Part III – Figure 1.31). They do not need mooring structures, but the spuds can damage bed protections. Harbour authorities can designate certain areas for vessels that will use their spuds.

In addition to a disembarkation facility, overnight stay harbours require some specific facilities, such as shore-side electricity, drinking water, and a car boarding facility (Figure 5.38). The car boarding facility can be a jetty or a pontoon. More details can be found in RVW (2020).

Figure 5.37: Lobith (NL), overnight harbour with floating landing stages (aerial imagery by the National Georegister (NGR) is licenced under CC BY 4.0).

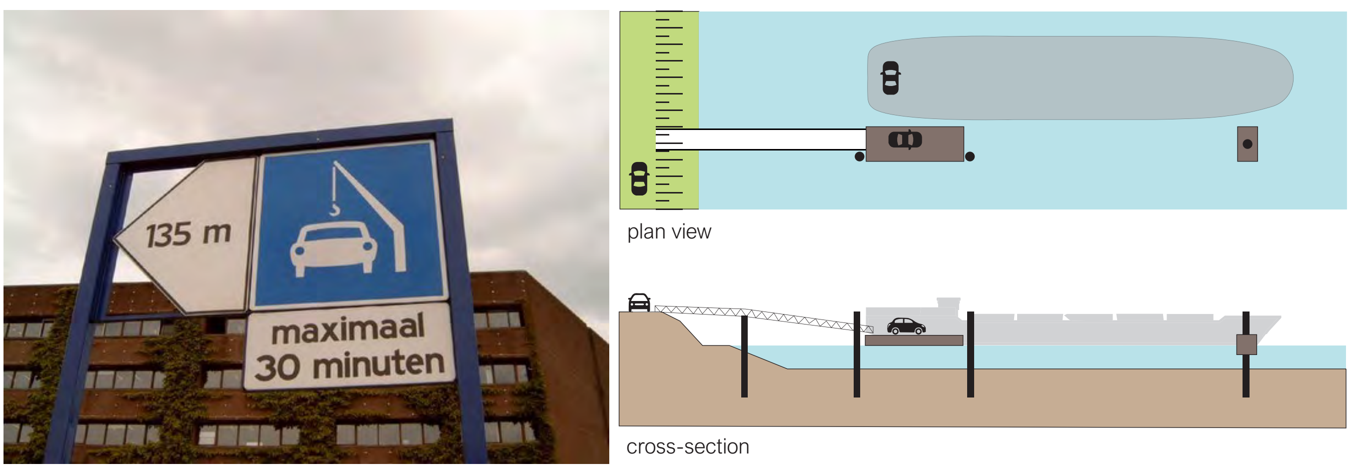


Figure 5.38: Car boarding facility with pontoon or landing stage for variable water levels (left: Indication for a car drop-off point by G.A.T. van Meegen, Nijmegen is licenced under CC BY-NC-SA 4.0, right: image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Apart from that, there are harbours providing temporary shelter, such as harbours of refuge (for wind and waves, floods, ice, or in case of machine breakdown), and service harbours (for survey vessels, contractor equipment, etc.). Further information can also be found in Part III – Section 2.4.

Part III

Waterways

1 Waterway transport

Sooner or later waterborne transport ends up in confined waters, be it a port access channel through a shallow coastal zone, the water bodies inside a sea port, or an inland port or waterway. If they form a properly functioning network, such waterways are not only important elements in the supply chain, but also drivers of economic development. They should therefore be designed carefully, so as to enable efficient, smooth and safe navigation. More than in deep open water, this requires insight into how vessels behave when sailing and interacting in confined water, including the pertinent hydrodynamic phenomena.

Part III Waterways focuses on these confined elements of the transport network, with the intention to enable students as well as professionals to perform feasibility studies, develop functional designs and carry out performance analyses.

Apart from the major inter-ocean canals, Figure 1.1 shows all elements of a waterborne transport network: from the port approach channel via the water bodies inside the port, the rivers and canals to the inland ports. All elements are necessary for efficient, reliable and safe transport and should therefore be considered in mutual connection.

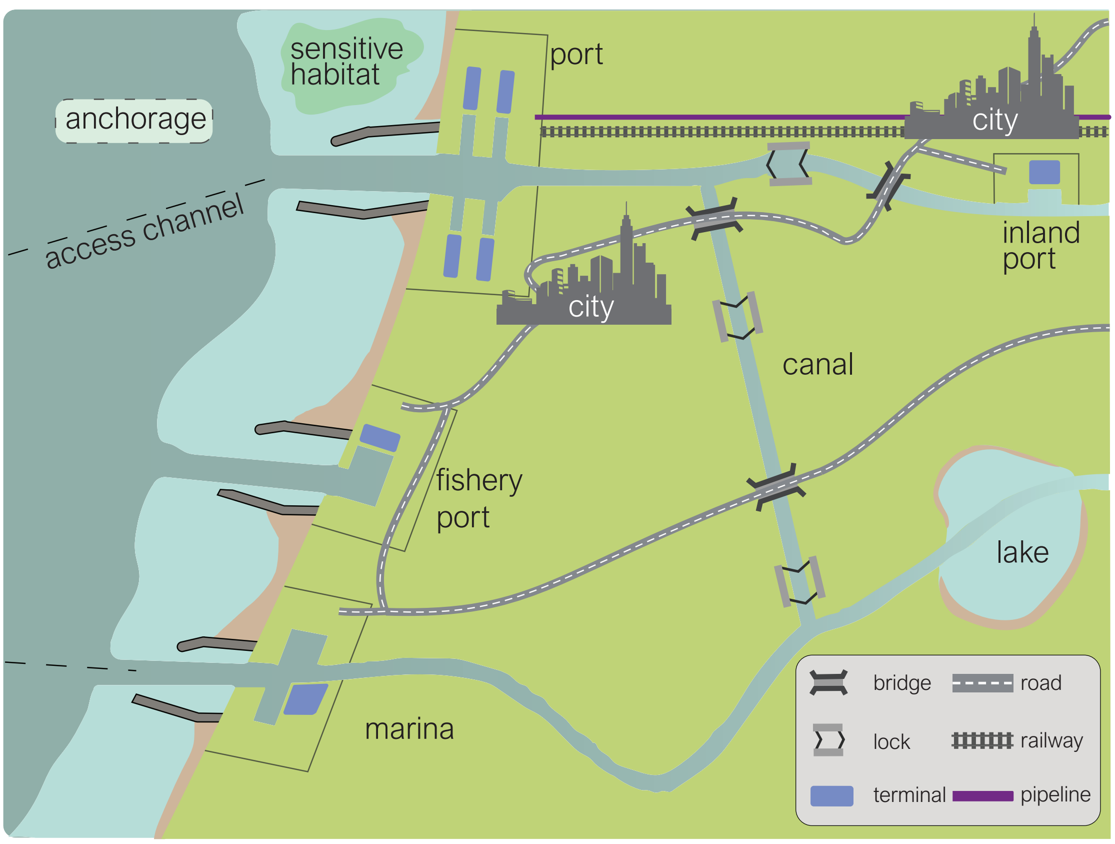


Figure 1.1: Elements of a transport network (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Starting point of such an integrated analysis is the supply chain. Considering inland transport as a chain of activities and facilities offers possibilities for analysis, optimisation and adaptation, similar to the supply chain approach for port terdateminals. Figure 1.2 shows the consecutive steps in the transport of cargo from a seaport terminal to a hinterland terminal. To establish the efficiency and effectiveness of this supply chain we need to understand the functioning of the individual elements and how they interconnect.

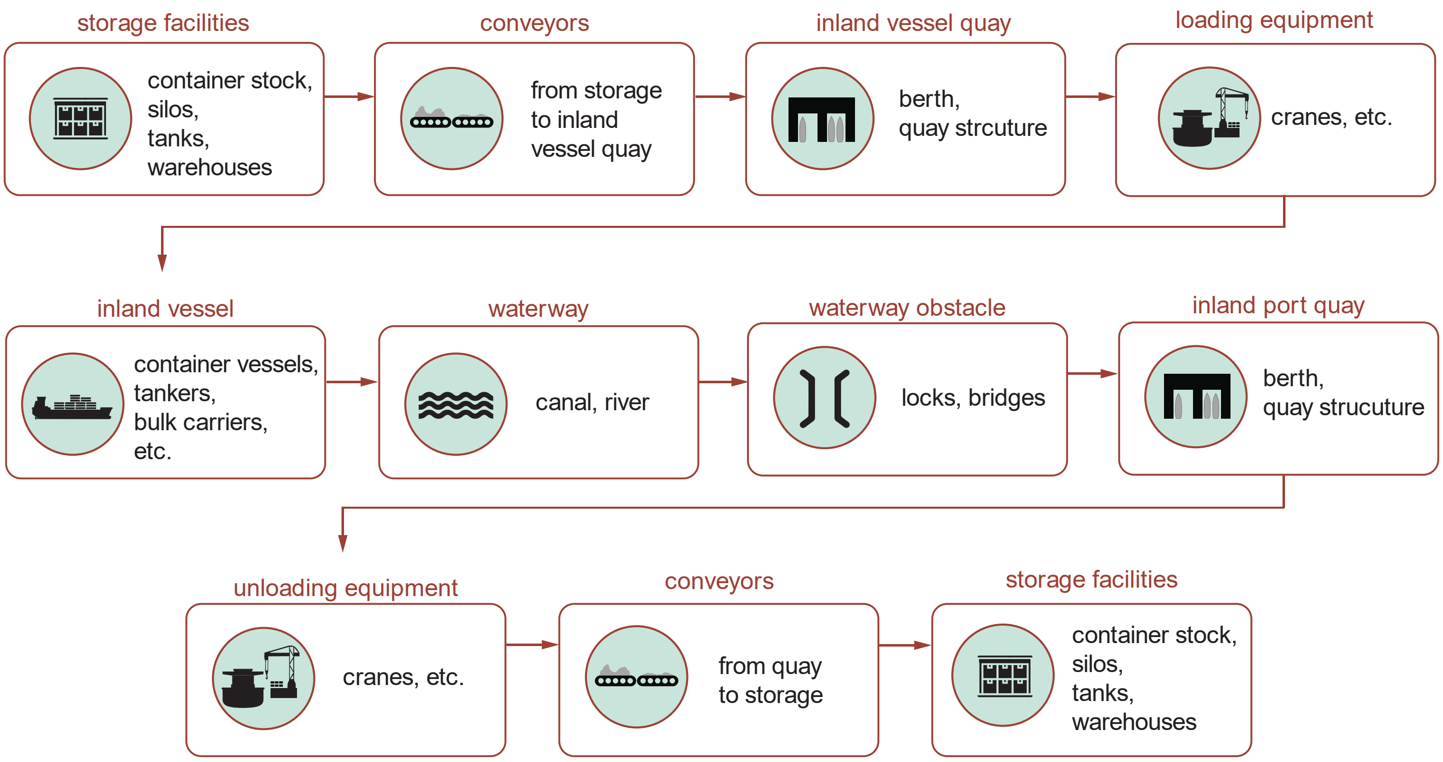


Figure 1.2: Supply chain for inland waterway transport (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Taking the supply chain as a starting point raises questions such as:

- What is the transport demand for each type of cargo (containers, dry bulk, liquid bulk, etc.)?
- What type of vessels are involved, considering cargo type (container vessels, tankers, dry bulk vessels, etc.), but also vessel dimensions (length, beam, draught, etc.)?
- What time to consider for mooring/unmooring?
- What time to consider for loading/unloading (type of equipment)?
- How many berths of what length are needed?
- How much loading/unloading equipment is needed to keep waiting times below the allowable maximum?
- How many conveyor belts/cranes are needed to move the cargo?
- How much storage capacity is needed, based on maximum call size and a maximum allowable dwell time?
- How many conveyor belts/cranes are needed to transport the arriving cargo to the hinterland stations?
- What is the length of the route over water?
- How do these vessels behave and interact when sailing in confined water?
- What are the required dimensions of the waterway?
- How do the properties and facilities of the waterway (water depths, currents, locks, bridges, bottlenecks, signs, signals, Fairways Information Services (FIS), Vessel Traffic Service (VTS), etc.) affect transport efficiency?

In Part II we have already addressed some of these questions, especially those pertaining to ports and terminals. Part III addresses those that concern waterways and vessel behaviour.

1.1 Importance of waterways

1.1.1 Historical background

Inland waterborne transport has been used already in ancient times to bring goods to and from the hinterland. Ancient Mesopotamia used the rivers Euphrates and Tigris for this purpose, Egypt the river Nile. The possibility of waterborne transport has brought great wealth and power to these civilisations.

Yet, rivers may not always be reliable as transport routes, sometimes even hazardous. In times of drought, the water depth may become too low for navigation, or the variable channel-shoal pattern involves the risk of grounding and accidents. Otherwise, currents can be dangerous and rapids may block further navigation upstream. Therefore, already in ancient times people began digging channels. In Mesopotamia, for instance, these were primarily meant for irrigation, but even then they were also used for navigation. In the 6th century BC the Persian emperor Darius I built the first canal primarily for navigation. It linked the Nile with the Red Sea and was meant to boost the economy of the newly conquered province of Egypt. The Chinese started building canals in the 3rd century BC, culminating in the so-called Grand Canal that connected the Yangtze River and the Yellow River. It was meant to bring agricultural products from the fertile Yangtze area to Xi'an, by the time the centre of power.

In the Netherlands the Romans built the Corbulo Canal, which connected the rivers Rhine (by the time debouching near the city of Leyden) and Maas (Figure 1.3). It was meant for commercial transport, as an alternative for the route via the hazardous coastal waters. The Romans built another system of canals in the area north of the Rhine, the Drusus Canals, but this was meant for military transport.

A canal also requires facilities to control the water level. Initially, this was done by weirs, with a gap in the middle that could be opened to let boats through. Clearly, this so-called flash lock works well in one direction, but not in the other. The Chinese engineer Chiao Wei-yo is said to have invented the pound lock in the 10th AD. The first European lock of this type is probably the one at Vreeswijk, the Netherlands, built in 1373 in a canal from city of Utrecht to the river Lek. Initially, the gates were simple flat structures that were raised and lowered when necessary. The idea of mitred gates, first applied in Milan round the year 1500 and still common in present-day locks, is attributed to Leonardo da Vinci.

From the 12th onwards, canals were built all over Europe, many of them in the Netherlands. The latter were primarily meant for drainage, with navigability as a welcome bonus. The transport network obtained in this way was an integral part of the region's economic development. The same is true for many other regions: economic development goes hand in hand with the availability of a good transport network.

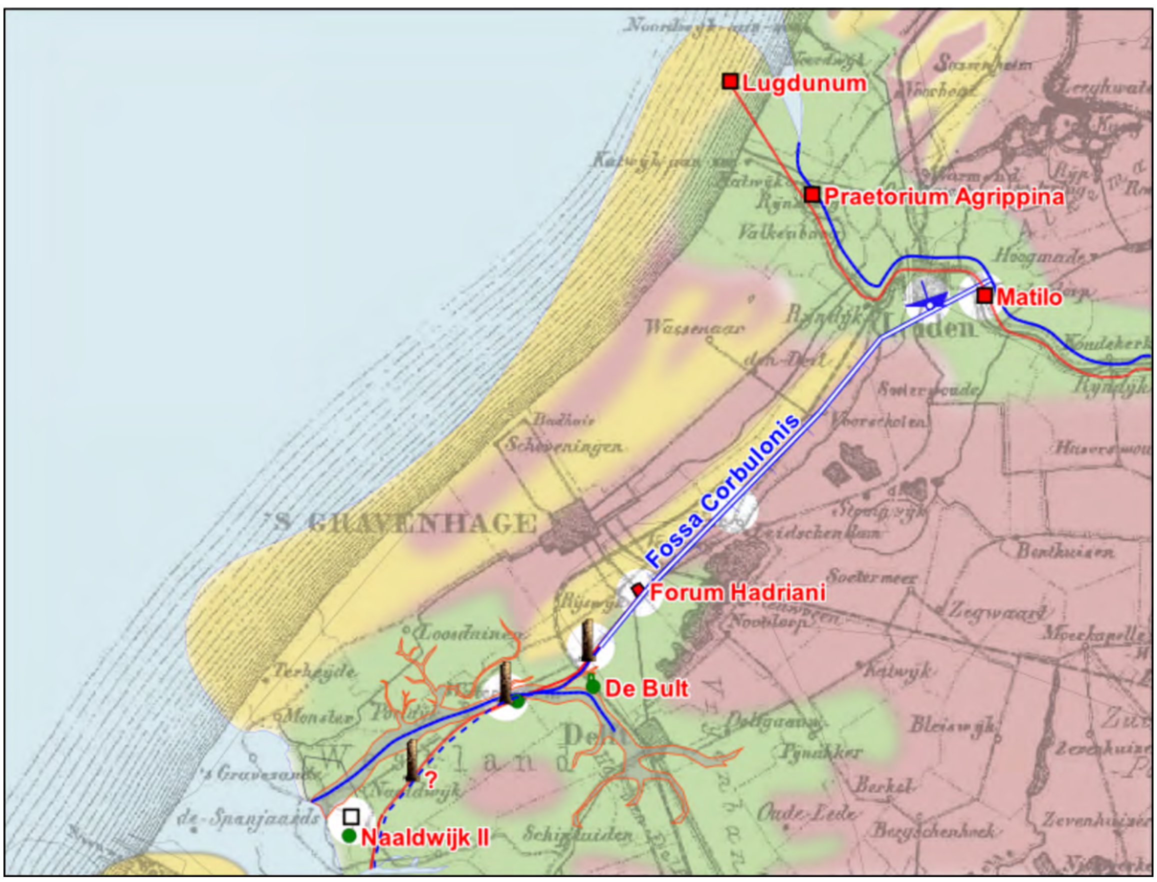


Figure 1.3: The Corbulo Canal built by the Romans and connecting Rhine and Maas (Fossa Corbulonis map by Hans Erren is licenced under CC BY 3.0).

1.1.2 Modern waterways

Two modern waterways are of paramount importance to overseas transport routes because they connect two oceans, hence shorten trade routes significantly. The Suez Canal connects the Indian Ocean, via the Red Sea and the Mediterranean, to the Atlantic Ocean, and the Panama Canal forms a shortcut between the Atlantic Ocean and the Pacific.

Figure 1.4: Route between Europe and Asia shortened by the Suez canal (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The Suez Canal was constructed by the Suez Canal Company between 1859 and 1869. It was officially opened on November 17^{th} 1869. It meant a radical shortening of the trade routes between Asia and Europe, no longer around Cape of Good Hope. A trip from a port in Western Europe to the Indian Port of Mumbai, for instance, was shortened by approximately 8.500 km from its original 20.000 km (Figure 1.4). The canal has no locks; the main limiting factor for the size of the largest passing vessels (Suezmax-class) is the Suez Canal Bridge. In 2015 the canal was expanded to allow for two-way traffic, which drastically enhanced its capacity. Environmental concerns have been raised, however, about the impact on the local population and the (increased) connection between the Red Sea and the Mediterranean sea, due to exchange of biological material. Moreover, the blockade between 1967 and 1975 forced oil transporting companies to develop Very Large Crude Carriers (VLCCs) in order to sail economically around the Cape again. These carriers, which are too large for the Suez Canal, are still in use, at the expense of the revenues from the canal.

After centuries of dreaming, decades of planning, and numerous failed attempts, the Panama Canal was successfully opened on August 15, 1914, with the passage of the cargo ship SS Ancon. It meant a major shortening of the trade routes (no longer around Cape Horn) between the Atlantic and the Pacific basins. The route between New York and San Francisco, for instance, was shortened from 22.500 km to 9.500 km. While this fact benefited many, it also caused a severe drop in traffic along Chilean ports due to shifts in maritime trade routes. The canal was a major engineering effort, with lock systems lifting the ships up to 26 m above sea level and down again (Figure 1.5).

Figure 1.5: The Panama Canal. Top: longitudinal profile; bottom left: the oldest Gatún locks (Atlantic lock system); bottom right: the newest Cocoli locks (Pacific lock system) (source top panel: Panama Canal Map EN by Thomas Rmer is licenced under CC BY-SA 2.0; source bottom panels: Panama Canal Gatun Locks opening by Stan Shebs is licenced under CC BY-SA 3.0 and ACP conceptual view of the Third Set of Locks 02 by Autoridad del Canal de Panama is licenced under CC0 1.0).

Note in the bottom right panel the water storage reservoirs next to the lock. Careful water management must prevent drainage of the entire Gatun Lake via the locks. The importance of the Panama canal is illustrated by the fact that its dimensions determined the design of a new class of ships, the Panamax class. Several years ago the Panama locks were upgraded to allow larger vessels to pass and this has led to another new class of ships, the New Panamax or Neopanamax class, which include large container carriers upto 14,500 TEU (366 x 49 x 15.2 m).

Figure 1.6: Network of 17^{th}-century boat-canals in the province of South Holland (image by Heritage House South Holland can be freely reused for non-commercial purposes, provided attribution is mentioned).

Also in the Netherlands canal building has had a huge economic impact. In the 17th century a network of boat-canals developed (Figure 1.6) which brought trade and wealth to the cities they connected. In that period Amsterdam was the most important commercial centre of the country, node in a thriving network of trade routes. The port was accessed from the North Sea, via the Texel inlet and the shallow Zuyderzee. The port of Amsterdam went on the decline when this tidal bay shoaled, the harbour silted up and vessel sizes increased.

After the French occupation, the newly appointed king decided to build an 80 km canal from Den Helder to Amsterdam, to improve access for seagoing vessels (Figure 1.7, left). This canal, built entirely by manpower, was completed in 1824, but functioned only for some 50 years. When after a few decades it became too narrow for the ever-larger vessels, it was decided to build a larger and much shorter (21 km) canal straight from Amsterdam to the sea, the North Sea Canal (Figure 1.7, right), finished in 1876. From an engineering point of view this was a particular challenge because the dune front had to be cut through and it was unclear what consequences that would have (also see Van de Ven, 2008). The North Sea Canal has allowed Amsterdam to maintain its position as an important port and trade centre. In 2022 a new larger lock will become operational.

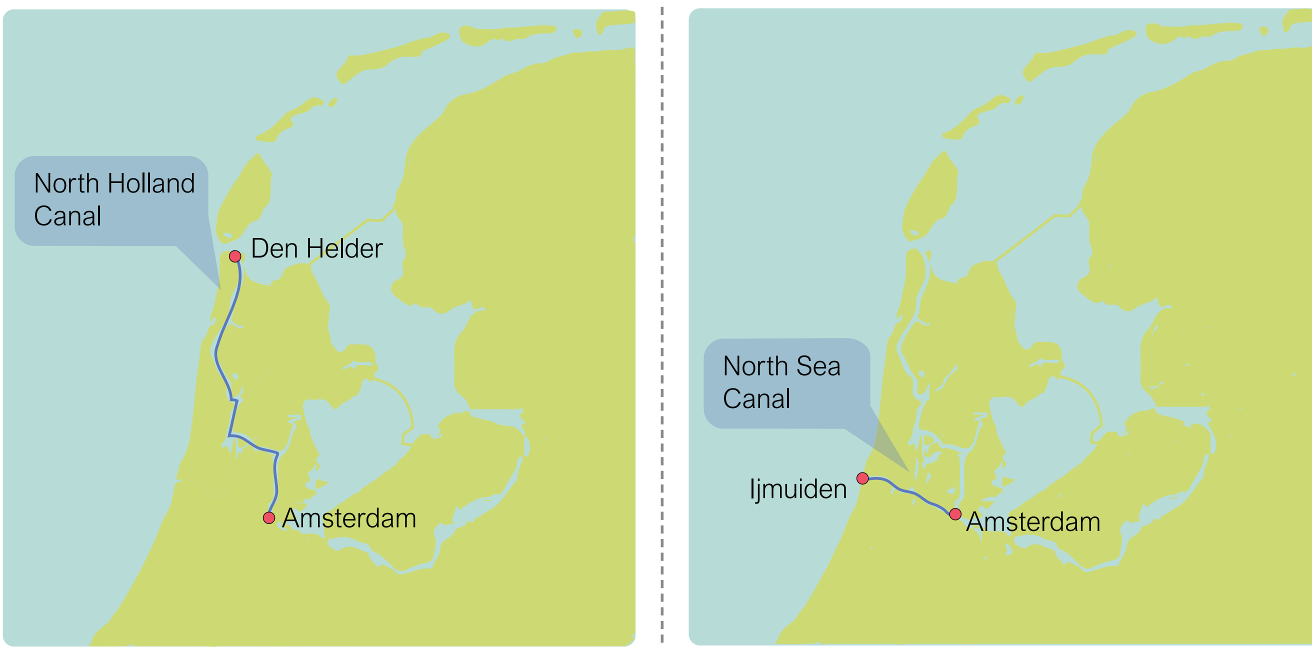


Figure 1.7: Amsterdam's connections with the sea; left: North Holland Canal; right: North Sea Canal (images by TU Delft – Ports and Waterways are licenced under CC BY-NC-SA 4.0).

At about the same time, the access to the port of Rotterdam became problematic. After a long and difficult process of trial, error and political deliberation, the shallow mouth of the river Maas was dammed and the Nieuwe Waterweg (New Waterway) was dug through the dune area. At the time (1865), Rotterdam was already an important port, due to its hinterland connection via the Rhine, but its deteriorating accessibility from the sea meant a disadvantage with respect to its main competitors, Antwerp and Hamburg. The new canal gave Rotterdam (and the economy of the Netherlands) a major boost, with it becoming the world's largest port in the second half of the twentieth century, and still the largest port of Europe at present.

1.1.3 Transport corridors

Another important category of waterways, next to big shortcuts of worldwide trade routes and canals giving access to ports, are those that together constitute Inland Water Transport (IWT)-corridors. Figure 1.8 shows the Northwest European waterway network used for container transport. The density of the terminals shows the importance of the north-south Rhine-Alpine corridor from the Netherlands into Germany and further south to the Alpine area (possibly to be extended to the industrial areas of France and Northern Italy).

Figure 1.8: Northwest European container transport network (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 1.9 shows, however, that this north-south corridor remains to be completed, just like several east-west corridors. Also note that Russia has a prominent corridor between Leningrad and the Black Sea, but no inland connection so far with the European network.

Figure 1.9: Major European corridors for waterborne transport (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

A new canal is under construction in northern France: the Seine Nord Europe Canal, part of a scheme to connect the Seine with the Scheldt, hence Paris with Antwerp and Rotterdam (Figure 1.10). This canal is aimed to be in use in 2022 and enable transport with larger vessels between these ports. Now the maximum load capacity is about 600 ton (European Conference of Ministers of Transport (CEMT) Class II). In the new situation the Seine-Scheldt connection is available for vessels up to 4400 ton and two-barge push-tow units (CEMT Class Vb), with single lane traffic on parts of the waterway. The goal of the new canal (estimated CAPital EXpenditures (CAPEX) 4.5 billion Euro) is to transport 12 to 25% of the current road transport over water. This will save 8 billion Euro (Present Value (PV)) of transport costs and is estimated to have an environmental benefit worth 2 billion Euro (less fuel consumption, fewer emissions, less traffic congestion).

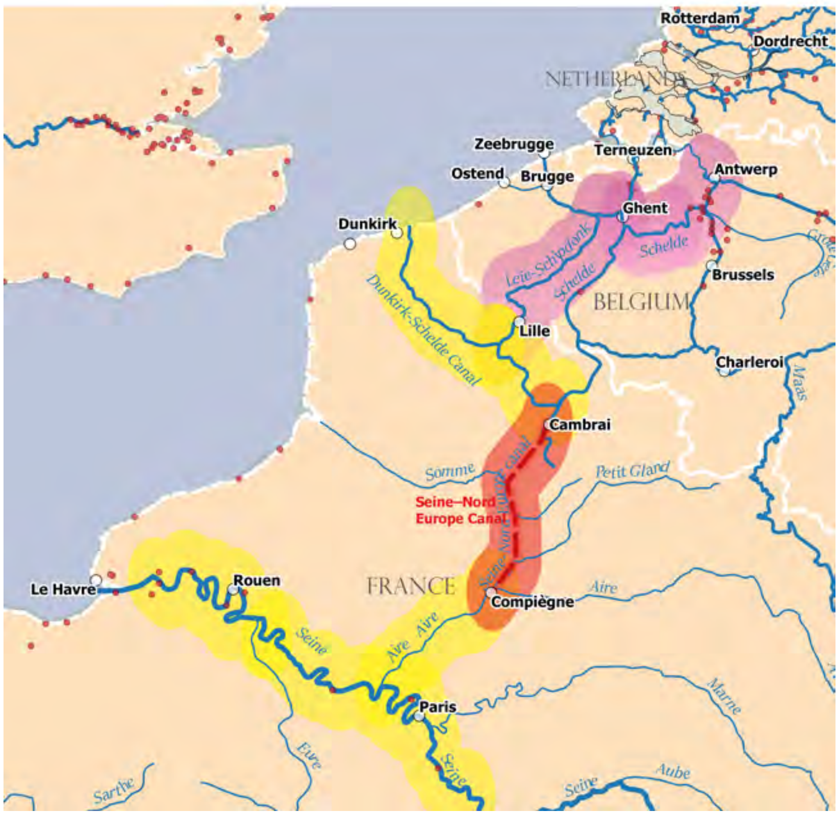


Figure 1.10: Seine-Scheldt corridor (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The Seine-Scheldt corridor is part of the so-called Trans-European Transport Network (TEN-T) in the European Union (EU). This is a planned network of roads, railways, airports and water infrastructure covering the EU, as part of a wider system of Trans-European Networks (TENs), including a telecommunications network (eTEN) and a proposed energy network (TEN-E or Ten-Energy). The TEN-T program provides clear policy guidelines for future modifications to transport networks, including those over water. The program makes clear which network connections are foreseen for the future, it provides clear guidance regarding the vessels to be accommodated by specific parts of the network, and provides policy guidance as to where inland ports and (un)loading facilities should be located. For practical reasons, the EU distinguishes a number of main corridors within the TEN-T network.

The Trans-European Networks initiative aims at an integral approach, optimising individual networks within the context of the entire system, all to the benefit of the Community as a whole. In Central and Eastern Europe the EU is presently planning a further extension of the waterway network, expecting it to significantly enhance the regional economy, hence the coherence of the Union.

A main issue for the proper functioning of corridors is that the service levels of the various elements should align. In practice this translates to waterway and infrastructure classification, which means that in a corridor that is supposed to be able to handle vessels up to a given class, each element in that corridor should at least be able to provide that service level. This applies to national corridors, but also to international ones, such as the Rhine Alpine corridor.

These international corridors require alignment of legislation, regulations and design standards. Lengthy bureaucratic border controls can significantly reduce a corridor's capacity, like in the case of the Danube. It is interesting to know that this cross-border alignment is not something that emerged only recently. Already since the 17th century, agreement on trade over the Rhine has been on the political agenda, albeit with varying degrees of success. In 1815 the freedom of international navigation on the Rhine, as well as a Central Commission for the Navigation of the Rhine (CCNR) to enforce that freedom, were established as part of the Final Act of the Congress of Vienna. In 1868 the Convention of Mannheim was signed, an international treaty between Baden, Bavaria, France, Hesse, the Netherlands and Prussia, to regulate vessel traffic on the Rhine.

The principles of the Mannheim Treaty are :

- free shipping;
- equal treatment between states, of sailors as well as fleet;
- exemption from shipping charges;
- simplified customs clearance;
- obligation to maintain the Rhine's banks;
- standardisation of ship safety and ship traffic regulations;
- a single jurisdiction for shipping matters and the establishment of Rhine waterway courts;
- a common procedure of appeal.

International corridors are connected with national networks. The Netherlands maintains eight national corridors. An analysis of supply and demand, and a decision on appropriate service levels, have led to a class definition for each corridor (see also Figure 1.11). National waterway management aims to ensure that the waterways function at the specified class level, regardless of varying conditions (such as high or low water levels).

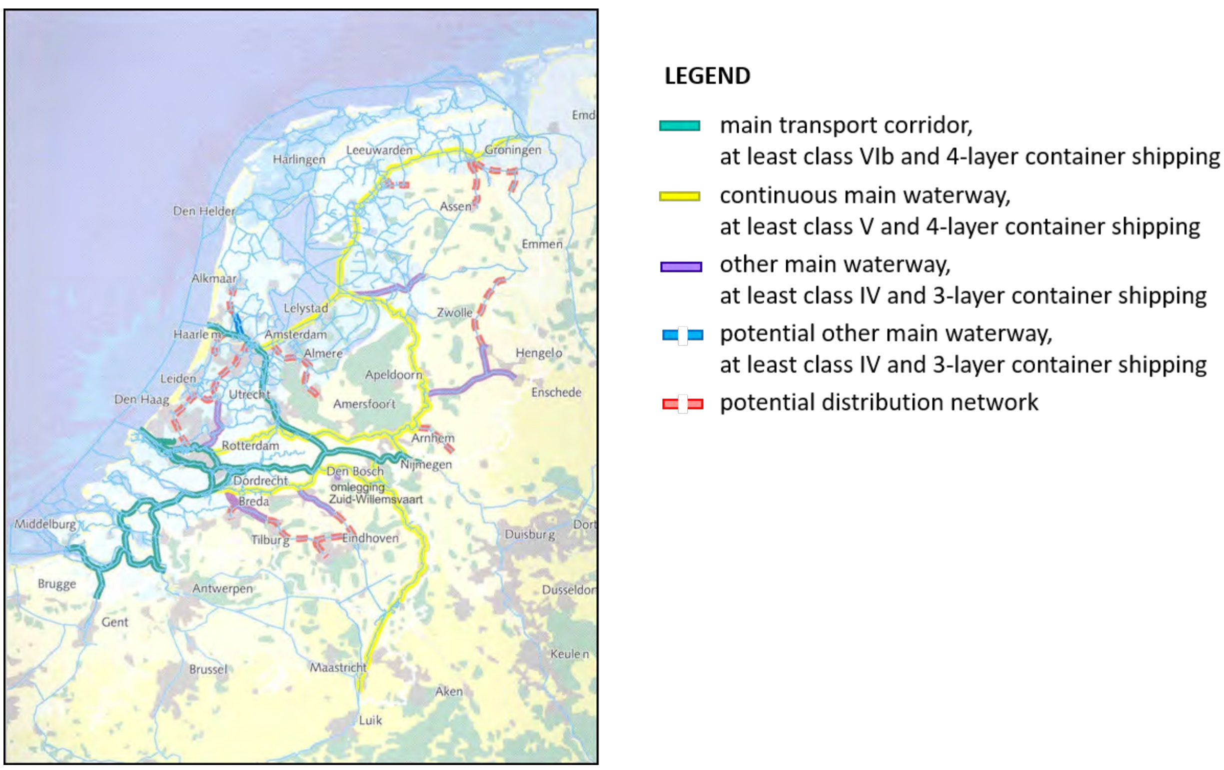


Figure 1.11: Envisage transport corridors in the Netherlands by 2020 (image from Min V&W, 2004, reproduction is allowed provided attribution is mentioned).

All this shows how important a well-functioning inland transport system is to the economic (and social) development of a country or region. A clever design of transport infrastructure, including waterway networks, can make a major difference to that development. Yet, this is not a trivial matter: it involves major investments over long periods of time in a context of large uncertainties. Strategic thinking, adequate information, careful analysis, smart engineering and sufficient adaptability are therefore key ingredients for success. In the following sections and chapters we will further discuss these matters.

1.2 Inland Waterway Transport networks

The previous section clearly illustrates that waterways form networks. An Inland Water Transport (IWT) network consists of:

- waterways;
- hydraulic structures, such as locks and bridges (movable and fixed);
- inland ports and IWT terminals;
- mooring facilities (quays, guiding structures, bollards and dolphins, et cetera); and
- service facilities, such as bunker stations.

The quality of the waterway infrastructure determines the efficiency and reliability of the supply chain. IWT may be compared as follows to the other modalities:

- the waterway dimensions determine the allowable size of the vessels (classification);
- presence of locks and movable bridges influences waiting times;
- available water depth and air draught of fixed bridges affects the load capacity of vessels;
- the presence of inland ports affects the efficiency of using the IWT mode compared to other modalities;
- the maintenance condition, equipment (buoys, signs, lights, presence of VTS) and the traffic support systems may influence the safety of navigation and the risk of accidents.

1.2.1 Classification of waterways

As indicated in the section on transport corridors, a main issue for the proper functioning of IWT networks is that the service levels of the various elements align. A common method to achieve this is to agree on a classification of waterways. A waterway may be attributed a certain 'class' when its dimensions allow vessels of a particular class to use them. A standard for classification agreed in Europe is the CEMT classification. The decision to what class

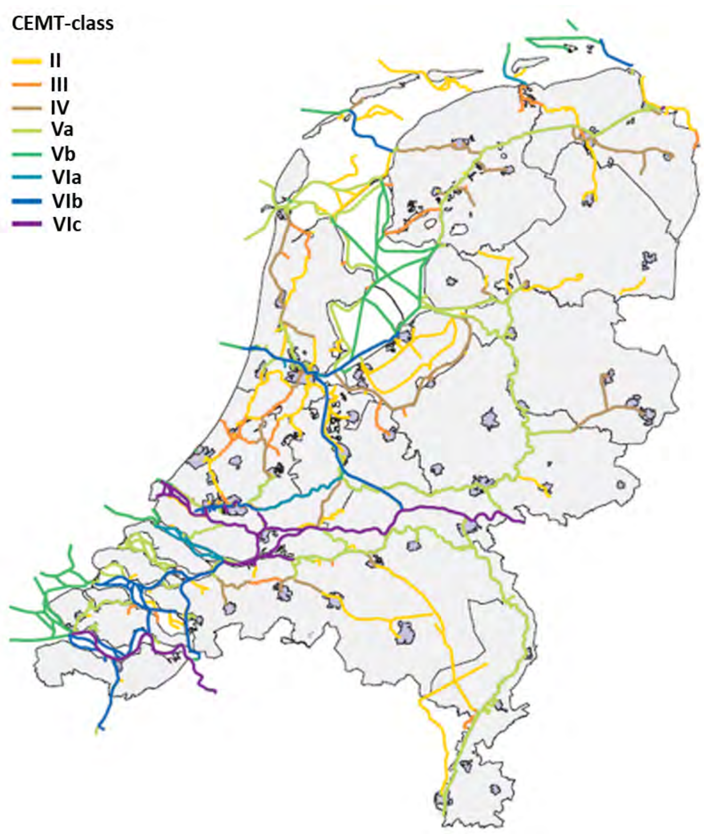


Figure 1.12: CEMT classification of inland waterways in the Netherlands (image from Min V&W (RWS-AVV) and CBS, 2003, reproduction is allowed provided the attribution is mentioned).

a waterway should be designed is based on the amount of cargo that is potentially transported on a particular route and the type of vessel that is foreseen to be the most appropriate to do this. Figure 1.12 shows the CEMT classification of the Dutch waterways.

1.2.2 Inland ports

Many municipalities have a port where one or more companies use the available quays and facilities. Inland ports have three functions:

1. node in a transport network;
2. location for industry and related services;
3. part of a production network.

Inland ports may have a local, regional or (inter)national function. Figure 1.13 shows the most important inland ports in the Netherlands.

Figure 1.13: Most important inland ports in Netherlands (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Table 1.1 gives an overview of the number of inland ports per province in the Netherlands. For more information: Nederlandse Vereniging van Binnenhavens (http://havens.binnenvaart.nl/home) and Bureau Voorlichting Binnenvaart (http://bureauvoorlichting binnenvaart.nl).

Province	Inland ports		
	Total number of ports	% of total	Number of ports with > 1 mln ton
Drenthe	6	2	1
Flevoland	7	2	0
Friesland	26	7	1
Gelderland	61	16	10
Groningen	21	5	1
Limburg	26	7	11
Noord-Brabant	39	10	9
Noord-Holland	51	13	7
Overijssel	25	6	3
Utrecht	21	5	1
Zeeland	19	5	5
Zuid-Holland	84	22	14
Total	385	100	63

Table 1.1: Number of inland ports per province (Korteweg and Kuipers, 2004).

A strategic position of inland ports with respect to the end destinations of the main cargo flows can mean the difference between IWT being the competitive transport mode or not.

1.2.3 Cargo flows

Figure 1.14 presents the inland waterborne cargo flows in Western Europe. It clearly shows that there still are several missing links in the European IWT network (also see Section 1.1.3). Filling these is likely to improve trans-European waterborne transport efficiency significantly and cause a change in modal split.

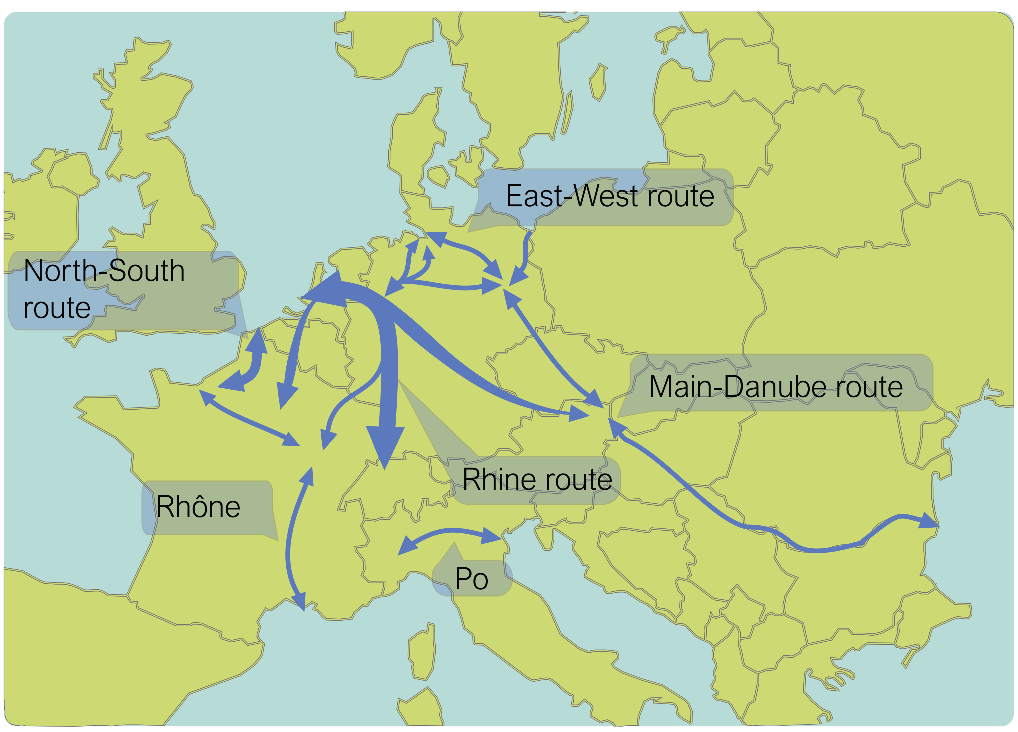


Figure 1.14: Waterborne cargo flows in Western Europe (adapted from Jimenez and Remác, 2016, by TU Delft – Ports and Waterways, licenced under CC BY-NC-SA 4.0).

Furthermore, the capacity of the existing waterway network is not fully used: on some routes 4 to 5 times more cargo could be transported. This could be even more if there were no bottlenecks such as locks and bridges.

Figure 1.15 gives an indication of the cargo flows in the Netherlands, showing that the export volume is dominant over the transit transport and transport inside the country. It also shows that by far the largest part of the cross-border outgoing transport goes to Germany and Belgium.

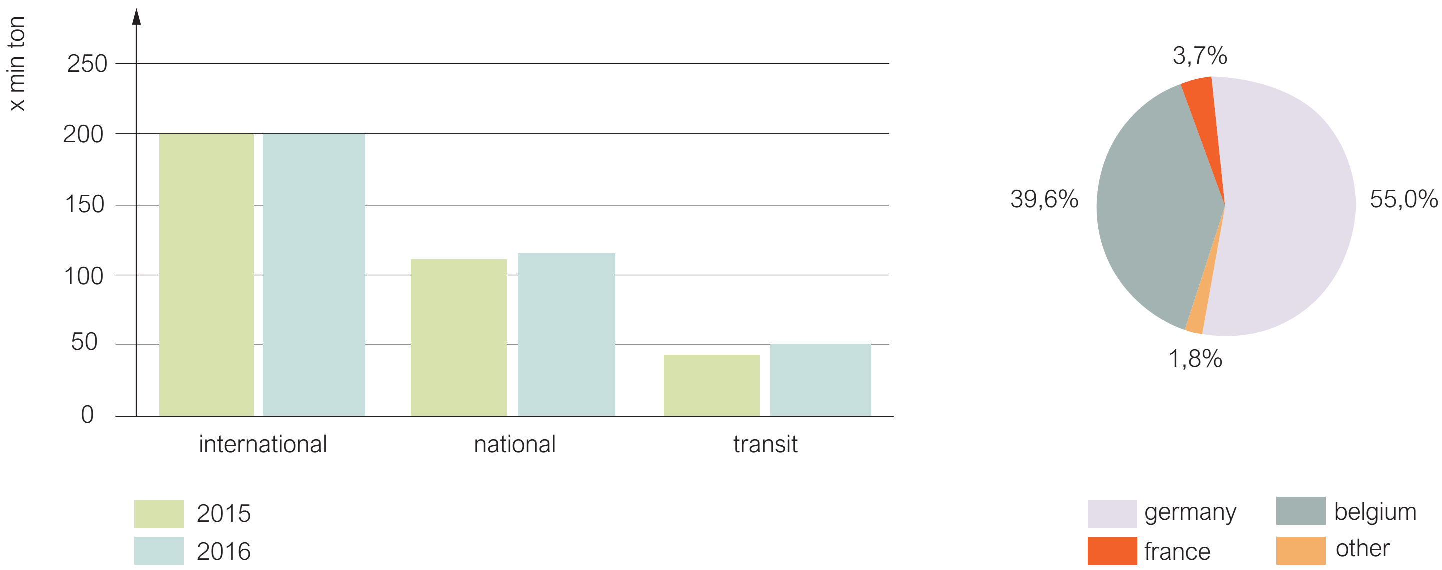


Figure 1.15: Inland shipping cargo flows in the Netherlands, by type (left) and by destination (right) (reworked from CBS 2017 by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Another relevant piece of information is how much inland shipping contributes to the total flow of goods. Figure 1.16 shows the modal split and the total amounts of cargo transported into, within and out of the Netherlands. The striking difference in the contribution of inland shipping between the incoming and outgoing cross-border cargo flows reflects the importance of the cargo flow from the Port of Rotterdam to the hinterland, especially Germany.

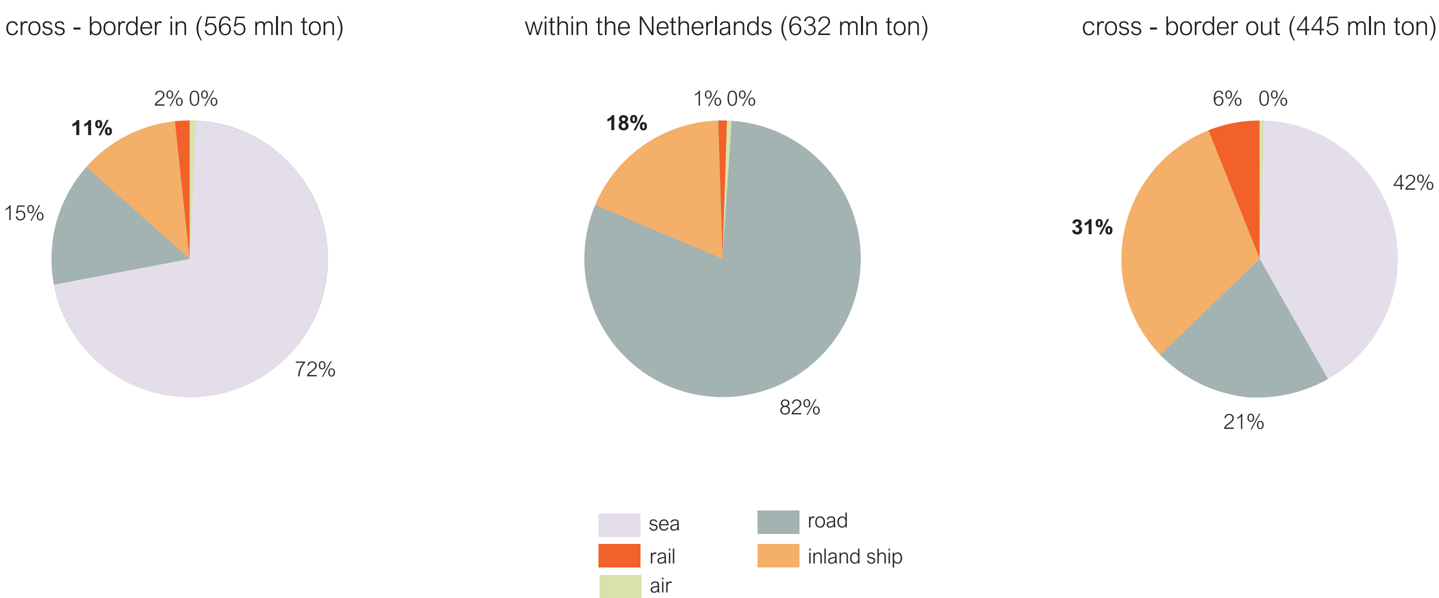


Figure 1.16: Modal split in the Netherlands, 2015 (reworked from www.schuttevaer.nl by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

In the Netherlands a relatively high percentage of the total IWT goes to the hinterland. Nevertheless, also in other countries there are ports with transhipment of cargo to inland vessels, as Table 1.2 and Figure 1.17 show for container transhipment.

Port	Transhipment volume (1000 TEU)			Modal split		
	Total	To hinterland transport	To inland shipping	Inland shipping	Rail	Road
Antwerp	8,176	7,824	2,618	33%	10%	57%
Hamburg	9,890	5,390	92	2%	34%	64%
Hongkong	23,900	unknown	2,700	unknown	unknown	unknown
Le Havre	2,638	1,880	259	9%	5%	86%
New Jersey	5,300	unknown	unknown	$< 1\%$	12%	87%
New Orleans	250	unknown	41	unknown	unknown	unknown
Rotterdam	10,790	8,200	2,500	30%	11%	15%
Shanghai	26,150	unknown	2,500	10%	1%	89%

Table 1.2: Container transhipment per port in 2007 (Kolkman, 2009).

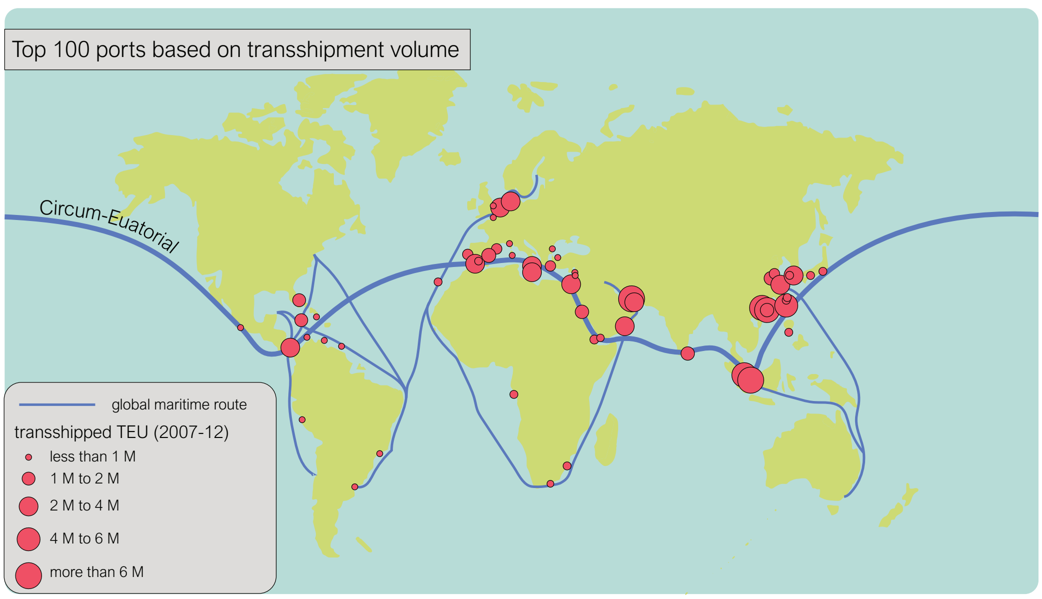


Figure 1.17: Transhipment of containers (reworked from http://www.porteconomics.eu by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

1.2.4 Multimodal and synchromodal transport

Much transport is multimodal, i.e. on the way to the destination there is a transfer to other another transport mode. A common form of transhipment follows the so-called hub-and-spoke model (Figure 1.18). It means that

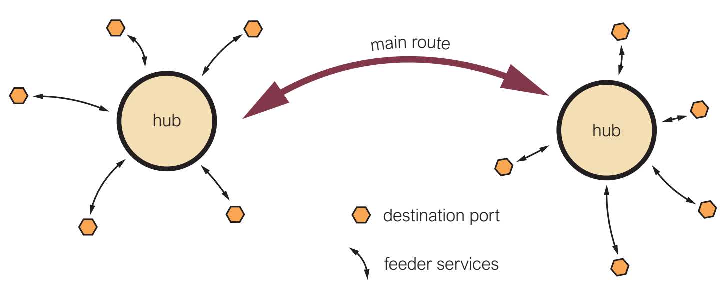


Figure 1.18: Hub-and-spoke model (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

vessels (or other transportation vehicles) collect their load from various terminals in a sea port (the hub) and bring it to a number of destination ports or end destinations inland, or the other way around (the feeder services).

This is also characteristic of the transport via the Rhine: vessels serve in general only a limited number of terminals, typically between one and five. At these terminals, containers are loaded for various seaport terminals, meaning that relatively many seaport terminals must be visited, on average nine terminals per trip. On the other hand, each seaport terminal is visited by inland vessels of different operators and coming from or heading for different destination ports. As a result, inland vessels spend a lot of time sailing between various terminals of a hub port and waiting to be served there. Figure 1.19, top, depicts this situation for container transport.

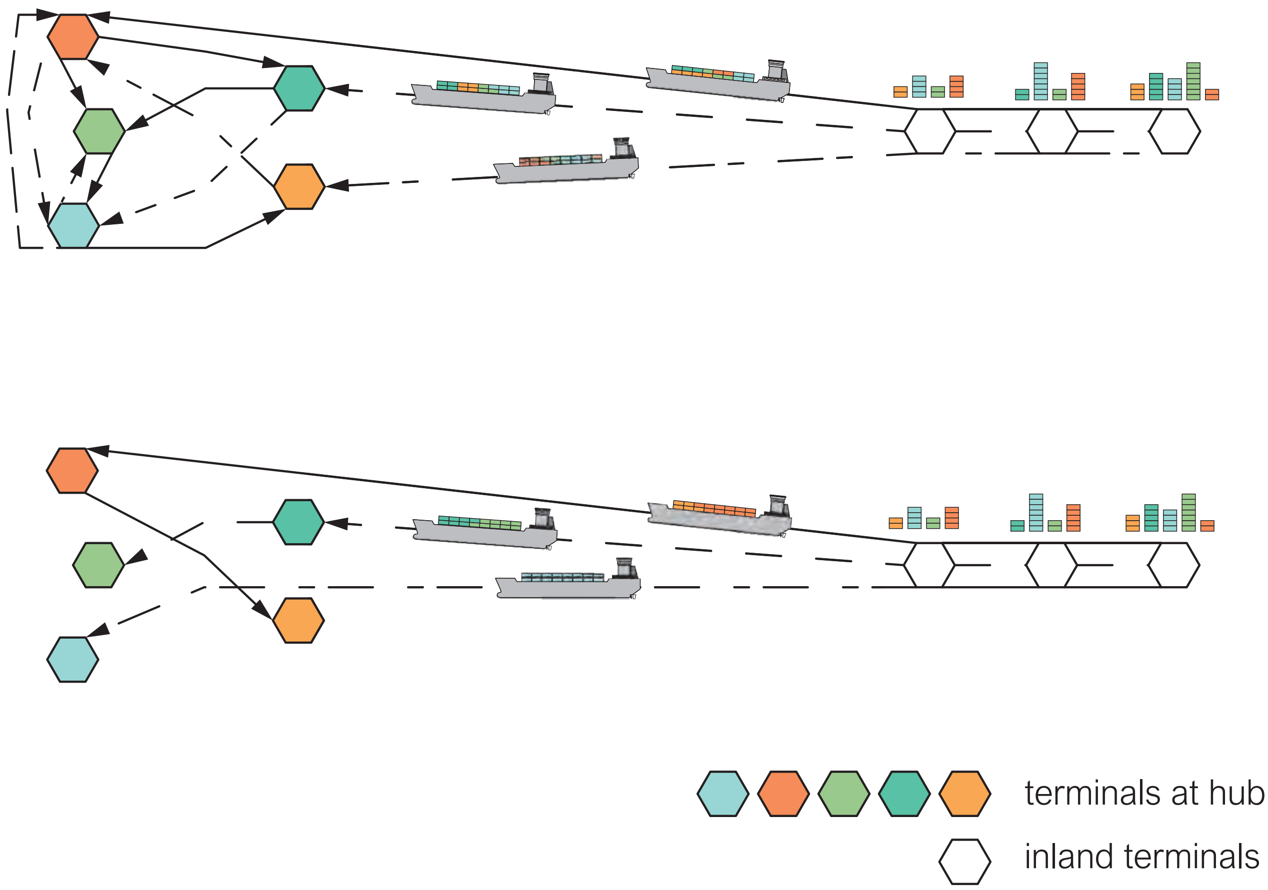


Figure 1.19: Loading- and unloading efficiency: present and desired state (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Port authorities recognise that the desired growth of container transport is jeopardised by congestion of inland vessels at seaport terminals. Inland container vessels are often loaded and unloaded at the same quays as sea-going vessels. Unlike sea shipping companies, those operating inland have no binding contract with the seaport or terminal authority. This may explain why, if a terminal is busy, sea-going vessels get priority, even if this leads to a suboptimal situation regarding the supply chain. The remedy may be a better planning of container transhipment in ports. Three aspects are important:

1. *Improved integral planning* – optimised planning of quay, crane and depot availability yields a better use of these facilities.
2. *Call optimisation* – bundling of containers per terminal, destination or vessel, will decrease the number of vessel calls while increasing the call size, thus enhancing the chain efficiency.
3. *Performance measurement* – monitoring of supply chain performance and individual actors, as well as the effect of measures taken, will enable a policy of gradual improvement.

The ultimate alignment of transport modes is called synchromodality. Here the transport chain stakeholders actively interact to enable real-time switching between transport modes tailored to make optimal use of available resources. Synchromodal transport is characterised by:

- optimal combination of modalities,
- flexibility to change (part of) cargo to another modality, and
- a virtual network with a supply chain director.

For the first practical experiences in the Port of Rotterdam, see Van Duin et al. (2019).

1.3 Commodities

In IWT we distinguish dry bulk, liquid bulk and container transport as well as passenger transport (Figure 1.20). Some characteristics of IWT in the Netherlands (Bureau Voorlichting Binnenvaart, 2006):

- It is market leader in international transport with a market share of about 60% of the total transported weight.
- It is market leader in bulk cargo transport, in particular for ore, coal, sand, gravel.
- It is market leader in chemical bulk transport, by lack of competition for this type of cargo.
- Inland navigation is strongly related to seaports. More than 60% of inland transport, mainly transit transport to and from the hinterland, finds its origin or destination in a seaport. For Maasvlakte 2 it has been agreed by contract that maximum 35% of the cargo shall be transport by road and 45% over water. For other ports there is no such agreement, because there it is easier to switch to another modality.
- Inland container transport has grown strongly over the last decennia. Most containers are transported by road but the share of transport over water has grown from about 15% in 1994 to about 33% in 2004 (measured in transported weight).
- IWT has no position in the transport of base- and end-products, it is rather a niche player in this field. The only exception is short-distance pallet transport, where in-time delivery is critical.

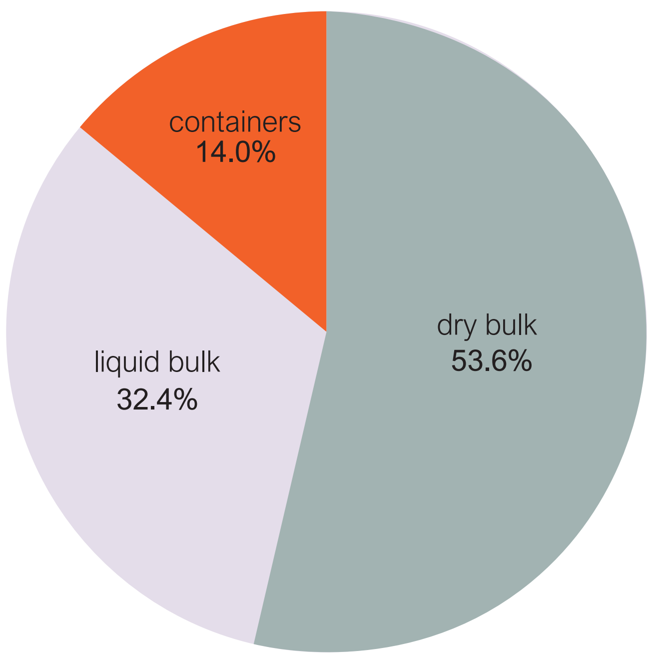


Figure 1.20: Cargo type percentages in the total IWT transport performance in tonkm in the Netherlands in 2019 (source: Eurostat, image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

1.4 Fleet

The West European inland fleet consists of more than 12,000 vessels (Table 1.3), of which 45% sails under the Dutch flag. The Dutch fleet sails mainly on the rivers in the Rhine and Maas basins. Unlike the situation in sea-going transport, a large part of the vessels is owned by individuals or families. The more than 250,000 recreational vessels in the Netherlands are not counted among the inland fleet.

Country	Vessel type					
	motor freighter	push barge	tugboat	push boat	motor tanker	tanker barge
Germany	887	758	122	226	366	41
Belgium	1,003	258	10	95	187	6
France	839	372	0	11	37	44
Luxembourg	7	0	3	7	15	1
Netherlands	2,740	998	408	593	839	18
Switzerland	14	2	4	2	50	3
Poland (2010)	71	571	17	192	0	0
Chech Rep.	32	119	83		0	0
Total	**5,593**	**3,078**	**564**	**1,209**	**1,494**	**113**

Table 1.3: West-European inland fleet composition in 2013 (Bureau Voorlichting Binnenvaart, 2017).

1.4.1 Inland vessel types

There are many types of inland vessels with a variety of shapes and sizes, mainly determined by the area of operation and the cargo type. The older ship types were named after a specific waterway or sailing area (Table 1.4). They all have their specific dimensions. For example, the Peniche (in Dutch: Spits) sails on the narrow French canals, in the southern part of the Netherlands and in Belgium. The Dortmunder is named after the German Dortmund-Ems Canal, the Rhine-Herne Canal vessel after the German Rhine-Herne Canal. The Europe vessel is built especially for the larger European rivers and canals. Nowadays, newly built ships are designed on the basis of operational area and the type of cargo, rather than for a specific waterway. They often have deviating dimensions.

Spits / Peniche vessel CEMT/RWS-class I/M1

Kempenaar CEMT/RWS-class II/M2

Dortmund-Ems Canal CEMT/RWS-class III/M4

Rhine-Herne Canal CEMT/RWS-class IV/M6

Table 1.4 – Continued on next page

Table 1.4 – continued from previous page

Large Rhine vessel CEMT/RWS-class Va/M8

Jowi-class CEMT/RWS-class VIa/M12

Table 1.4: Motor vessels.

In 1954 an international classification system (CEMT classification) was introduced which divides the waterways into five classes depending on the horizontal dimensions. Starting point of the system were the dimensions of five ship types frequently sailing at that moment in Western Europe. The latest classification according to this system is known as CEMT 1992.

In 2002 the Dutch authorities concluded on the basis of an analysis (Min V&W (RWS-AVV), 2002) that the dimensions in the CEMT-table were no longer representative of the West European fleet and did not reflect that ships were made longer while keeping the same standard beam. Obviously, the tonnage increased. Moreover, the loaded draught proved to be larger than given in the CEMTtable. Therefore, a new and more detailed vessel classification was introduced, the AVV-2002 table (Min V&W (RWS-AVV) and CBS, 2003).

CEMT	AVV-2002	Name	B_s (m)	L_s (m)	D_s loaded (m)	max. load (ton)	air draught (m)
	M0					1-250	
I	M1	Spits / Peniche	5.05	38.5	2.50	251-400	5.25
II	M2	Kempenaar	6.60	50-55	2.60	401-650	6.10
III	M3	Hagenaar	7.20	55-70	2.60	651-800	6.40
	M4	Dortmund-Ems	8.20	67-73	2.70	801-1050	6.60
	M5	Dortmund-Ems elongated	8.20	80-85	2.70	1051-1250	6.40
IVa	M6	Rhine-Herne	9.50	80-85	2.90	1251-1750	7.00
	M7	Rhine-Herne elongated	9.50	105	3.00	1751-2050	7.00
Va	M8	Large Rhine	11.40	110	3.50	2051-3300	9.10
	M9	Large Rhine elongated	11.40	135	3.50	3301-4000	9.10
VIa	M10	Reference vessel	13.50	110	4.00	4001-4300	9.10
	M11	Reference vessel	14.20	135	4.00	4301-5600	9.10
	M12	Rhinemax	17.00	135	4.00	> 5601	9.10

Table 1.5: RWS 2010 for motor vessels (RVW, 2020).

CEMT	AVV-2002	Arrangement	B_s (m)	L_s (m)	D_s max (m)	max. load (ton)	air draught (m)
I	B01		5.20	55	1.90	0-400	5.25
II	B02		6.60	60-70	2.60	401-600	6.10
III	B03		7.50	80	2.60	601-800	6.40
	B04		8.20	85	2.70	801-1250	6.60
IVa	BI		9.50	85-105	3.00	1251-1800	7.00
Va	BII-1		11.40	95-110	3.50	1801-2450	9.10
	BIIa-1		11.40	92-110	4.00	2451-3200	9.10
	BIIL-1		11.40	125-135	4.00	3201-3950	9.10
Vb	BII-2l		11.40	170-190	3.50-4.00	3951-7050	9.10
VIa	BII-2b		22.80	95-145	3.50-4.00	3951-7050	9.10
VIb	BII-4		22.80	185-195	3.50-4.00	7051-12000	9.10
VIc	BII-6l		22.80	270	3.50-4.00	12001-18000	9.10
VIIa	BI-6b		34.20	195	3.50-4.00	12001-18000	9.10

Table 1.6: RWS 2010 classification for pushed convoys and coupled units (RVW, 2020).

Compared to the CEMT-table the classification presents a larger number of subclasses. After additional studies of large ships by MARIN, the AVV-2002 table has been transformed into the RWS 2010 classification, which is included in detail in the Guidelines for Waterways 2020 (Table 1.5 and Table 1.6 provide a reduced representation).

For the dimensions of motor vessels, push-tow units and coupled convoys (two coupled motor vessels or a motor vessel coupled with one or more barges, see RVW (2020) for the classification table) the more detailed AVV-2002 is recommended for research, predictions, and statistical interpretations. Table 1.7 shows examples of push-tow units and coupled units.

Besides motor vessels, push-tow units and coupled units, also river cruise vessels, ferries and recreational craft are sailing on the European waterways.

Push boat

Push boat

Table 1.7 – Continued on next page

Table 1.7 – continued from previous page

Barge CEMT-class Va

Coupled unit CEMT-class Vb

4-barge push-tow unit CEMT-class VIb

6-barge push-tow unit CEMT-class VIIa

Table 1.7: Push-towing and coupled units.

1.4.2 Developments of the inland fleet

The inland fleet is continuously developing and renewing itself, but it takes a long time due to the long life-cycle of vessels and engines. Recent developments are:

- changes in steering devices and installed power;
- increase in scale: decreasing number of small vessels (CEMT classes I to III) and increasing number of large vessels, particularly CEMT-class V and higher (new length 135 m; new beam 14.20 and 17 m);
- increasing total load capacity;
- conservation and renewal of smaller vessels which can reach destinations on smaller waterways;
- growing share of double-hull tankers for safety reasons;
- more strict emission requirements;
- on-board Information and Communication Technologies (ICT), such as River Information Services (RIS);
- use of light-weight materials in shipbuilding; lighter vessels are of interest for smaller waterways (Policy Research, 2007);
- new ship types, such as the NeoKemp (a modern type of Kempenaar), the AMS barge, the INBI vessel, and the riversnake push-tow unit;
- diversification of the fleet (fast vs. slow; large vs. small; multipurpose vs. specific cargo), on the one hand; strong specialisation (cargo type and transport relation) due to market segmentation (CCR, 2002), on the other.

As a consequence, small inland vessels seem to be pushed into a niche market (Buck Consultants International, 2008), larger vessels being cheaper per ton cargo, easier to finance and more attractive for the skipper (as they offer more space for living). These larger vessels, however, cannot reach every destination: about one-third of the 14,000 km long waterway network in the Netherlands, Belgium, Germany and France is only accessible for vessels up to 1,500 ton and 85 m long.

Other consequences are:

- less efficient locking in locks that have not been designed for these large vessels,
- heavier collisions due to extra mass, and
- bridge passages become more critical, due to the larger beam.

River cruise vessels

Renewal is also taking place in the river cruise fleet. Every year a number of new large and very luxurious river cruise vessels appear, especially in the Rhine/Main/Danube region (Figure 1.21). Many of these vessels have been built in the Netherlands.

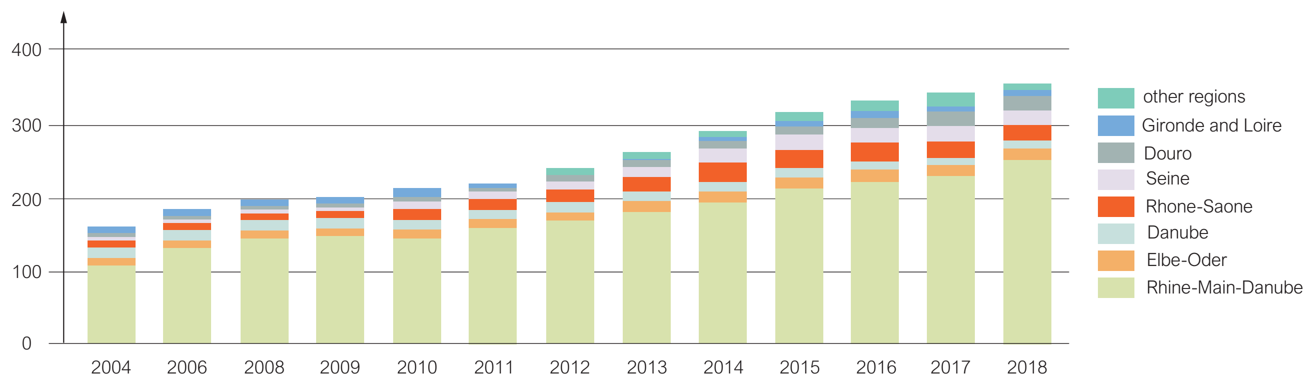


Figure 1.21: River cruise fleet per region (reworked from Hader, 2018, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Tankers

The discussion on environmental safety of single-hull tankers has a large impact on this fleet. The reason is a number of environmental disasters with sea-going tankers, such as the “Erika” and “Prestige”. These disasters resulted in world-wide public and political discussions about the use of single-hull tankers. As a consequence, also inland tankers also change to double hulls, although environmental disasters with inland tankers have never occurred. Since big oil companies required transport by double-hull tankers, many large inland tankers (> 5,000 ton) have been built. In the Netherlands they are mainly used in the Amsterdam-Rotterdam-Antwerp area (ARA-area). In 2011 a still larger inland taker was introduced: the Vorstenbosch, with dimensions 147.5 x 22.8 x 5.4 m) and a load capacity of 13,300 ton (source: Bureau Voorlichting Binnenvaart, 2020). This vessel also operates mainly in the seaports and the ARA-area.

Container vessels

About 40% of the container transport within the Netherlands is carried out by inland vessels. There are over 50 inland container terminals in Northwest Europe and still new ones are being realised. An increasing network of efficiently operating terminals will stimulate the regional distribution of cargo by inland transport. Furthermore, a scale increase in container vessels can be observed. Around 2005, the maximum capacity of inland container vessels was 200 TEU (3500 ton), with vessels dimensions of 110 m length, 11.40 m beam and 3.5 m draught. Since then vessels heve been built with capacities up to 500 TEU (4,000-5,000 ton) and dimensions of 135 m length, 14 – 17 m beam and 4 m draught (Figure 1.22).

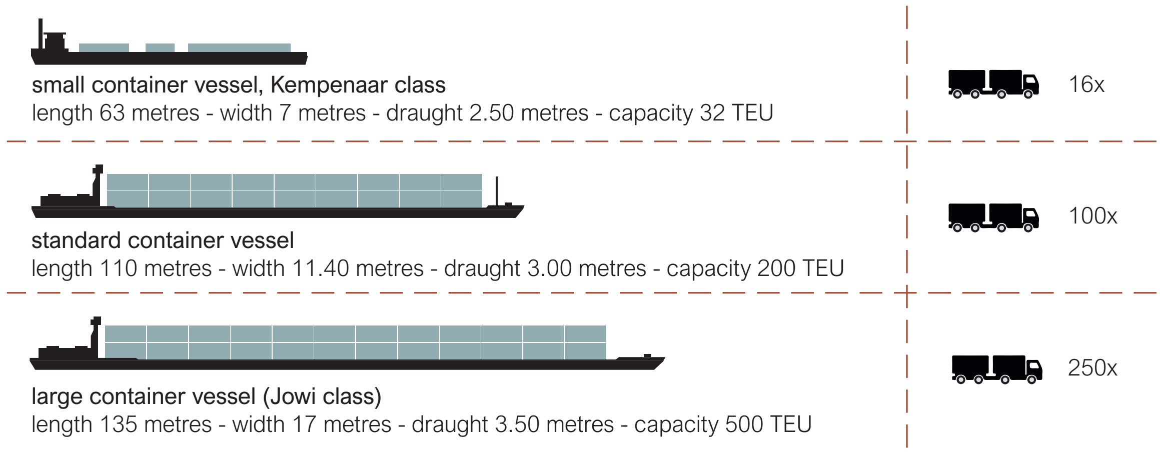


Figure 1.22: Modern inland container vessels (reworked from Bureau Voorlichting Binnenvaart, 2006, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The Neokemp (see Figure 1.22, top panel, for the dimensions and loading capacity) was designed in the year 2000 for small waterways with fixed and low bridges. The steering house, located at the front, can be lowered to pass low bridges and raised to overlook the containers (Figure 1.23).

Figure 1.23: Neokemp container vessel (by S.J. de Waard is licenced under CC-BY-SA-3.0).

In practice, it is very important to develop a good business case before building these new smaller vessels, because there can be a strong competition with older vessels, which are often written off.

Beam of container vessels

Most vessels (80 m long, 9.5 m wide) can have three containers next to each other in stacks of three layers. The standard class Va vessel (110 m long, 11.4 m wide) is often adjusted to four standard containers next to each other and four layers high (200 TEU). There is a demand, however, for a larger width in order to place four pallet-wide containers next to each other. This would require a beam of 12.0 m (Van Dorsser and Verheij, 2016).

Since the 1990s also coupled units are used (up to 800 TEU). The largest container vessel type nowadays is the Ursa Montana (Figure 1.24), specially designed for coupled units. Its dimensions are 193 x 17.3 x 4.1 m, its maximum load 5,400 ton. Coupled convoys can be up to 190 m long and 14, 17, 20 or 22 m wide. With a draught up to 4.0 m these vessels can transport 5,000, 7,000 or 9,000 ton, respectively, corresponding to about 300, 500 or 800 TEU. Dry bulk (container) vessels wider than 18m are not active yet, probably because the container or river terminals along the Rhine are not suitable for them.

Figure 1.24: The coupled unit Ursa Montana transports 712 TEU (400 × 40-feet high cube containers) (from binnenvaartkrant.nl, "800 TEU in één keer", Copyright by Binnenvaartkrant).

Container vessels with on-board crane

The costs of cranes on terminal quays can be avoided if the container vessels can load and unload themselves. An example of a container vessel with an on-board crane is the crane barge, an innovative inland vessel with its own crane that can transport 130 TEU, see Figure 1.25.

Figure 1.25: Crane barge with its own crane (MCKS Mercurius by Mercurius Group is licenced under CC BY-NC-SA 4.0).

Estuarine shipping

Since about 2010 navigation with strengthened inland vessels takes place on a route between the Belgian ports of Oostende and Zeebrugge and the mouth of the Westerschelde, see Figure 1.26.

Figure 1.26: The Deseo on the Westerschelde (Maassluis 8-6-2019 by kees torn is licenced under CC BY-SA 2.0).

This so-called estuarine shipping improves the accessibility of coastal ports. The Flemish sea ports are connected via waterways with the hinterland, but their capacity is insufficient (see, for instance, www.wenz.be). At the moment there is no estuarine shipping by Dutch vessels, but it can become relevant because of the growing transport of oil products between the northern and southern sea ports of the Netherlands. Container transport between Maasvlakte 2 and Antwerp may also be interesting. It requires new regulations for inland vessels adapted for estuarine shipping along the coast. So far, skippers have to observe the International Convention for the Safety of Life at Sea (SOLAS) rules, which are mandatory for all international trips.

1.4.3 Vessel characteristics

This paragraph will discuss some important terms related to ship dimensions, the propulsion system and the rudder system (Figure 1.27). This is relevant for computations of the ship-induced water motions, ship speed and performance of IWT regarding emissions, et cetera (see Part IV).

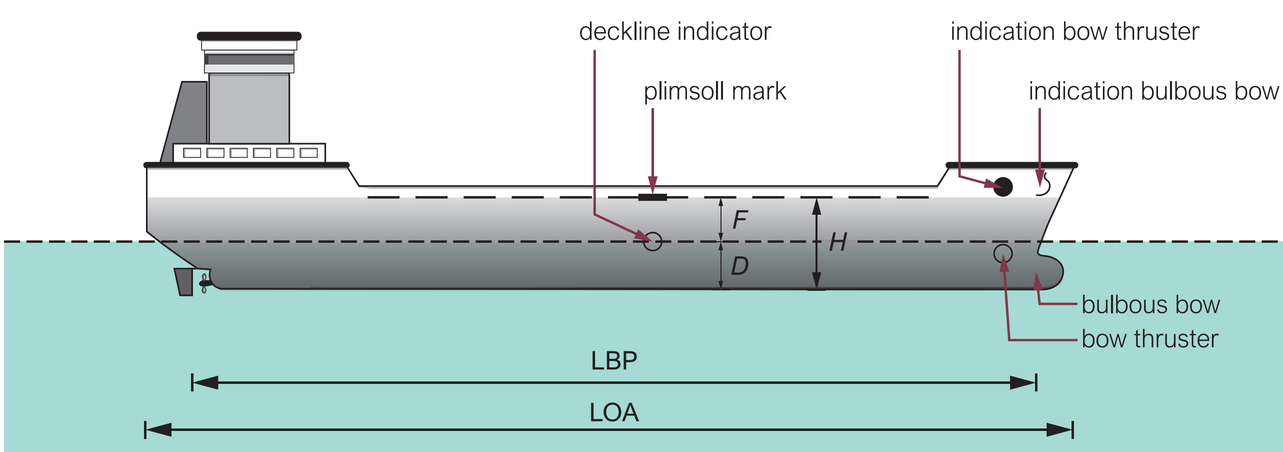


Figure 1.27: Ship characteristics (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Ship related terminology

- *carène* – shape of the immersed part of the ship's hull;
- *displacement* (∇) – displaced water volume, so the volume of the carène. Often expressed as mass of displaced water (Δ);
- *amidship section* – largest cross-section of a ship;
- *waterplane* – intersection between the surface of the water and the hull. The loaded waterline is the waterplane when the ship is loaded;
- *freeboard (F)* – distance from the top of the deck to the waterplane;
- *length between perpendiculars* (L_{BP} *or* L_{PP}) – the horizontal distance in metres between (1) the point of intersection of the ship's bow and the waterline when fully loaded, and (2) the vertical line through the axis of the rudder of the ship;
- *length over all* (L_{OA}) – distance between the front point of the bow and the backside of the stern;
- *length at the waterline* (L_{WL}) – distance between the points of intersection of the ship's bow and the ship's stern with the waterline when fully loaded
- *beam* (B_s) – maximum width of the ship;
- *draught* (D_s) – distance from waterplane to the bottom of the keel;
- *air Draught* (D_{air}) – distance from waterplane to the highest point above the waterplane;
- *sheer line depth (H)* – vertical distance between the bottom of the freeboard deck and the top of the keel;
- *cargo capacity* – the weight of the cargo;
- *block coefficient* (C_B) – this dimensionless coefficient determines the slenderness of the ship. A low value represents a slender hull shape and a higher value a fuller, more blunt shape.

$$C_B = \frac{\nabla}{L_{BP} \cdot B_s \cdot D_s} \tag{1.1}$$

Shape of the vessel and block coefficient

The design of the bow of the ship in particular is of great influence on the resistance encountered during sailing. A streamlined ship will encounter less resistance than a rectangular barge. On the other hand, a rectangular barge has a larger load capacity. Therefore, depending on the intended route, a compromise will have to be reached between load capacity and navigation speed. The design of ships thus varies from very blunt-shaped vessels (Peniche) to a very streamlined design (Danube pull-tow units).

The block coefficient (Equation 1.1) expresses the relative importance of resistance, viz. the larger the coefficient is, the more resistance the vessel will encounter. Table 1.8 gives the block coefficients for a number of vessel types. For longer ships the block coefficient may approach 1, since the influence of the bow and the stern of the ship decrease correspondingly.

Vessel type	**Block coefficient (C_B)**
Container vessel	0.65 - 0.70
Bulk carrier	0.70 - 0.80
LNG tanker	0.75 - 0.80
Inland motor vessel	0.80 - 0.95
Barge of a push-tow unit	0.96 - 0.99
Tug	0.45 - 0.50
Tug for sea-going vessels	0.50 - 0.60

Table 1.8: Block coefficients (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Propulsion

Most conventional inland vessels have one (main) propulsion system. Larger motor vessels (engine power over 750 kW) are often provided with two propellers. Depending on the installed engine power, modern push boats are provided with two or three propellers, placed in nozzles. The diameter of the propeller is about 2 m. To estimate the required power the following rule of thumb is used: engine power in HP = 1.3 to 2 times the load capacity in tons. The factor 1.3 applies to conventional vessels, the factor 2 to tankers and push barge units. Another rule for cargo vessels says: average power is about 0.5 kW per ton load capacity with a standard deviation of 20 to 30%. Note that part of the installed engine power is used for systems on board, such as heating and lighting (hotelling part). This is relevant for speed and emission computations (see Part IV – Chapter 5).

Characteristic values of installed engine power in inland vessels are are (MARIN, 2008; PIANC, 2008a):

- *dry bulk vessels of the Dortmund-Ems Canal type and Rhine-Herne Canal type* – 1 (sometimes 2) propellers of 1.2 to 1.6 m diameter; installed propulsion power 550 to 750 kW; installed bow thruster power about 250 kW (standard deviation 30%);
- *modern, newly built vessels of the Rhine type and Rhinemax type (length 110 to 135m)* – usually 1 and, sometimes 2 propellers in a nozzle of 1.6 to 1.8 m diameter; installed power 900 to 2800 kW; installed bow thruster power up to 700 kW (standard deviation 30%);
- *container vessels (400 TEU; length 135m)* – 2 propellers in a nozzle with a diameter of 1.6 to 1.8 m and an installed power of 2000 to 3400 kW; equipped with 2 bow thrusters;
- *pushers* – 2 or 3 propellers in nozzles with a diameter of 2.7 m and an installed power of 900 to 2800 kW; 1 or 2 bow thrusters or flanking rudders;
- *river cruise vessels* – 2 or 3 propellers in nozzles with a diameter of 1.6 to 1.8 m and an installed power of 800 to 1400 kW; equipped with 2 bow thrusters;
- *tugs* – 2 propellers in nozzles with a diameter of 1.6 to 1.8 m and an installed power of 800 to 1000 kW; equipped with 2 bow thrusters.

Regarding steering devices and installed power, we see that nearly all new vessels are equipped with bow thrusters, and that the installed power is increasing for the main propulsion system as well as the bow thrusters.

Bow thrusters

Most inland vessels are equipped with a bow thrusters nowadays; 95% of motor vessels of the classes IV and higher has such thrusters. The manoeuvrability of a vessel at low ship speeds is improved considerably by bow thrusters, which is important in waiting areas at locks and bridges, and at quays. They also increase safety and manoeuvrability in narrow canals or rivers. Three types of bow thruster systems are used for inland vessels, viz. the transverse jet system with four distinct outflow openings (Figure 1.28), and the steering roster and compound jet, both with 360° turnable outflow in the ship's keel (Figure 1.29).

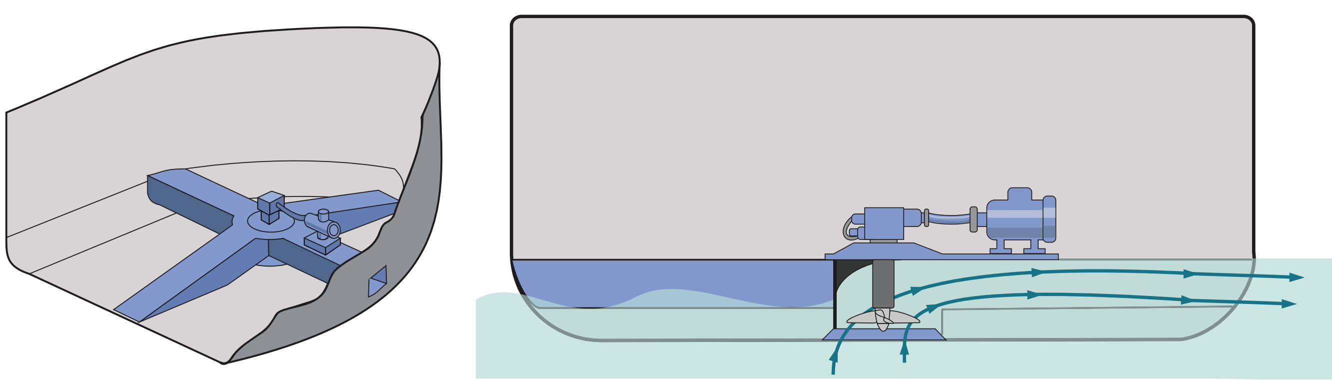


Figure 1.28: Bow thruster, type transverse jet with intake in the vessel's keel (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

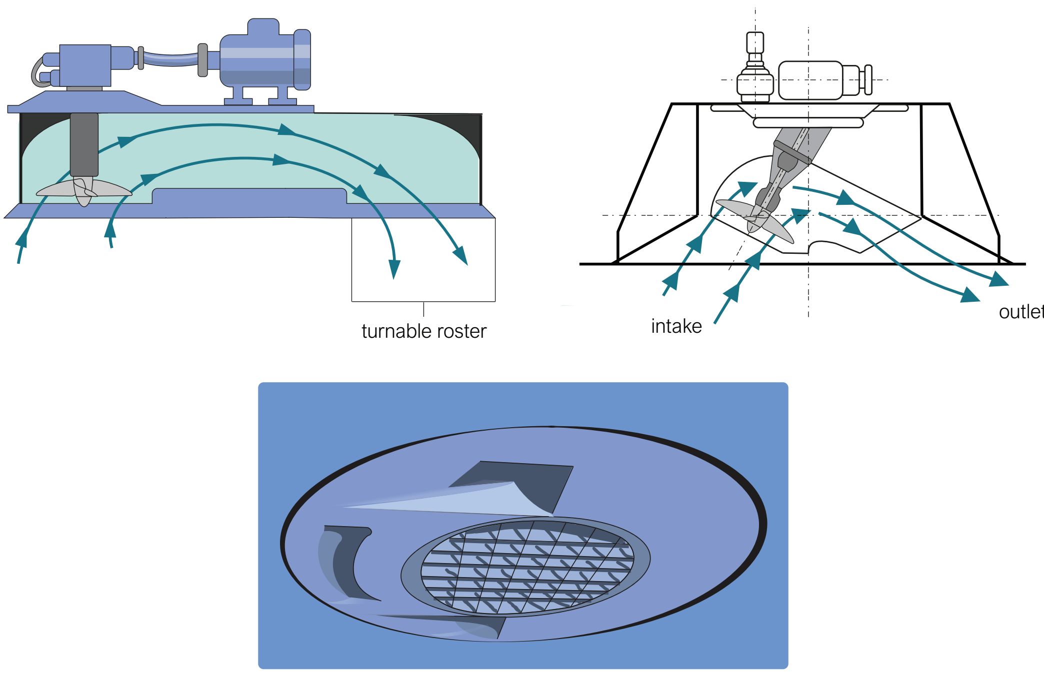


Figure 1.29: Bow thruster, type compound jet (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The larger the installed power, however, the more an unprotected berth bottom will scour during mooring and unmooring, or the heavier the bed protection required. In windy stretches of canals and rivers, where bow thrusters are used to keep the ship on course, bank protection may also be necessary. Even protections on top of pipelines and tunnels have to be checked for the higher flow velocities and turbulence levels in the propeller and thruster jets.

Rudder system

The functioning of the rudder can be explained in a somewhat simplified manner as follows (Figure 1.30). A pressure (F_p) exists due to a rotation of the rudder over an angle δ_r and has its point of impact in the pressure point at a distance (e) from the front of the rudder. This force can be resolved into a rudder resistance (F_L) parallel to the ship's axis and a transverse force (F_T) perpendicular to this axis. The transverse force (F_T) will

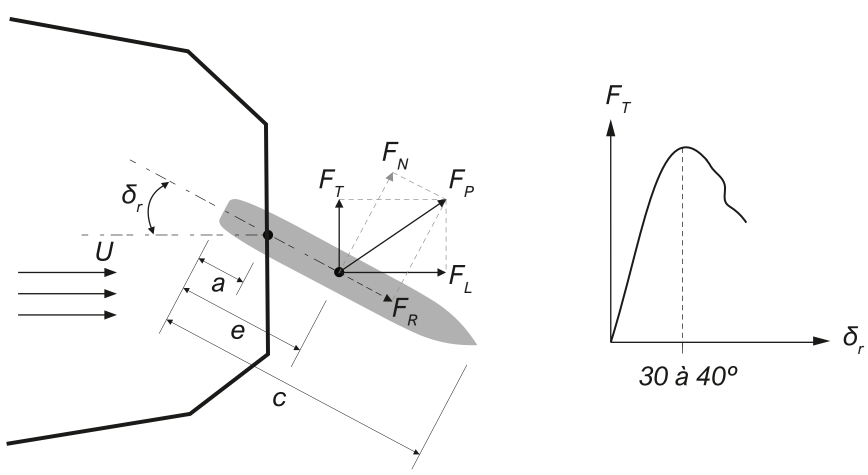


Figure 1.30: Principle of rudder system (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

push the stern of the ship to the right (starboard), while the bow will steer left (port side). The rudder resistance causes the ship to slow down. The size of these forces depends on the rudder type and the current velocity of the water. The more propulsion power is transferred into transverse force power, the more efficient the rudder is.

The two most familiar rudder systems are the singular rudder and the multiple rudder. For better operation and smaller rudder forces a multiple rudder is used. More information on rudders can be found in maritime manuals (see for example: Molland and Turnock, 2007).

Head rudder

The modern inland vessels have such large dimensions that one stern rudder system is seldom sufficient. To enhance manoeuvrability a head rudder can be applied (Figure 1.31). A small rotation of this device causes a considerable moment around the ship's centre of gravity. With head rudders it is easier to stay on course when approaching a lock, to manoeuvre when coupling barges in a current, or to hold the course of an empty vessel in cross-wind. Nowadays, most vessels use bow thrusters instead of a head rudder.

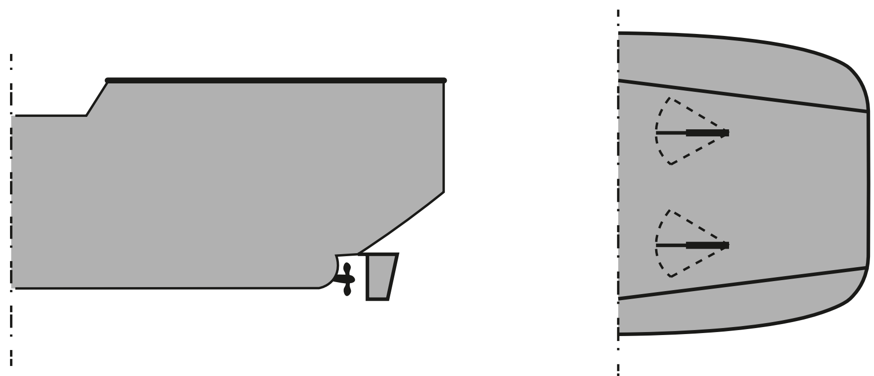


Figure 1.31: Head rudder (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Spuds

In inland navigation the use of spuds is increasing. A spud is a vertical vertical pipe that can be pinned into the channel bottom. A clever combination of spuds enables vessels to fix or moor themselves (Figure 1.32). The use of spuds has the advantage of less CO_2 emission, less time needed for mooring and unmooring in waiting areas at locks and bridges and central control of the vessel from the steering room without interference of the crew. A possible disadvantage of spuds is damage to bed protections and the risk of puncturing the impermeable layer. Spuds cannot be used in areas with a rock bottom, like in the German Rhine.

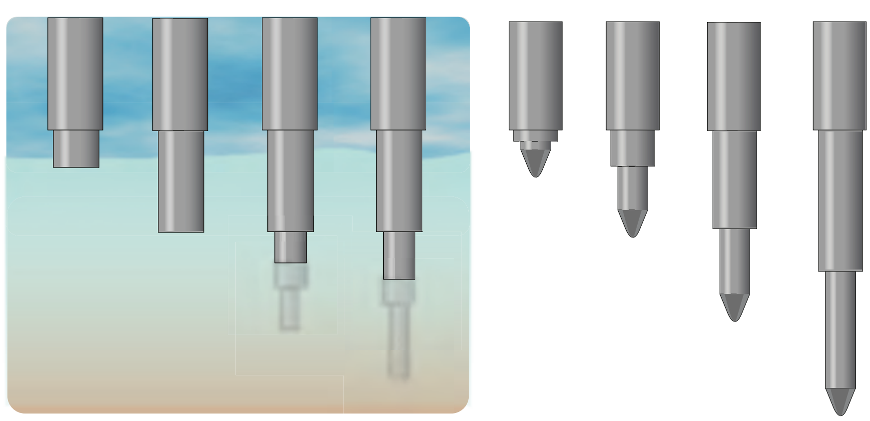


Figure 1.32: Spuds of the telescope type (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

2 Dimensions of waterways

[1]Waterways are generally confined areas through which vessels can sail. Apart from inland waterways (rivers, canals, navigation channels through shallow inland lakes), they also include port access channels and water bodies in ports. In this chapter we will consider the dimensions of waterways required for efficient, smooth and safe navigation. First, we will present design rules given in PIANC manuals and other guidelines (e.g. RVW, 2020). Secondly, we will provide information regarding simulation models and nautical safety analysis to be used in the conceptual and the final design phase respectively for port access channels, port water areas, and inland waterways.

2.1 Ship behaviour and ship-ship interactions

Apart from rudders, propellers and thrusters, there are external factors influencing the behaviour of a ship, such as wind, currents, and waves. A skipper has to take them into account when negotiating the limitations and complexities of a waterway and the interaction with the other traffic on it. But they are also factors to be considered when designing a waterway.

Basically, the motion of a ship on open water has six components, or degrees of freedom: three translational and three rotational (see Figure 2.1). The ship movements are the result of the interaction between the vessel and its surroundings. The ensuing water motion in confined water, is different from that in open water. The same goes for the interaction with other ships sailing nearby. These effects also have to be taken into account when determining the dimensions of a waterway.

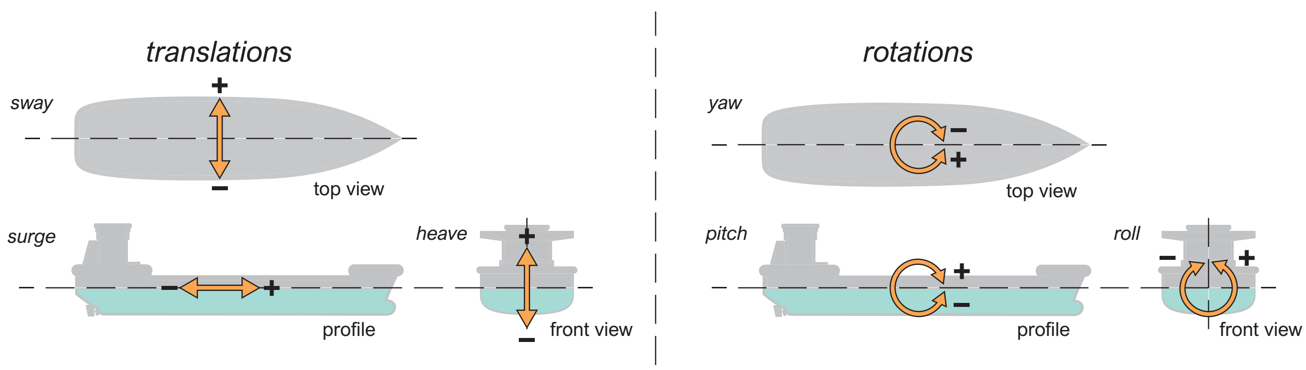


Figure 2.1: The six degrees of freedom of ship motion (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The terminology of Figure 2.1 is mainly used for ship motions in waves. For ships sailing on inland waterways the following terms are used (also see Figure 2.2):

- *sinkage* – the constant downward displacement of the ship's centre of gravity (comparable to heave which is the wave-driven, and therefore dynamic downward movement due to waves),
- *trim* – the rotation about the horizontal axis perpendicular to the ship (comparable to pitch); trim can be caused by the ship's speed, as well as by uneven loading,
- *heel* – the rotation about the longitudinal axis (comparable to roll), usually caused by uneven loading but can also occur when a ship is sailing in a bend.
- *squat* – the combination of sinkage and trim as far as it is caused by the ship's forward speed (note that trim may also be caused by uneven loading).

[1]This chapter made use of '*Inland Waterways. Ports, Waterways and Inland Navigation*' (Verheij et al., 2008), lecture notes for the Ports and Waterways course CIE4330 at TU Delft.

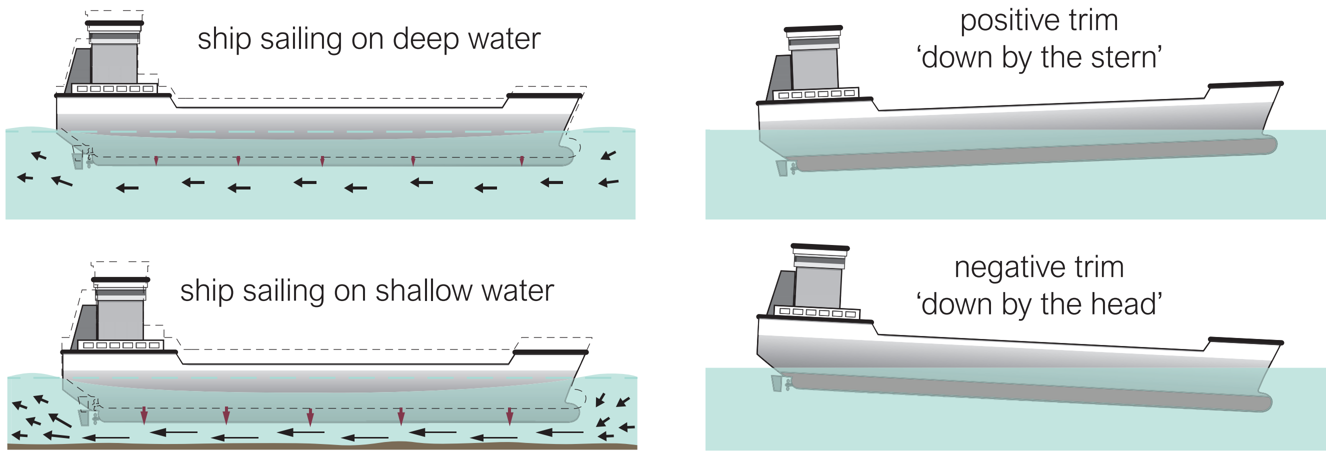


Figure 2.2: Sinkage (left) and trim (right) of a ship (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Sinkage is a constant displacement (under constant conditions) in contrast to 'heave', which is wave-driven and therefore dynamic. Heel also occurs when a ship navigates in a bend. In confined water sinkage and trim cause a decrease of the effective nautical depth, which may influence the ship's manoeuvrability or even lead to grounding.

In the following sections we will describe how the principal dimensions of a waterway depend on ship behaviour and ship-ship interactions.

2.1.1 Standards for the waterways depth

The depth required for waterway navigation depends on the draught of the reference vessel and its motions, which can be influenced by a range of factors (Figure 2.3).

The depth/draught ratio h_0/D_s determines the manoeuvrability of the ship. The minimum required depth of a waterway is mainly determined by the permissible draught and the speed of the design ship. In favour of a good controllability the Under Keel Clearance (UKC) cannot be taken too small. Therefore, the water level depression caused by the ship's speed relative to the water is an important parameter to judge the UKC.

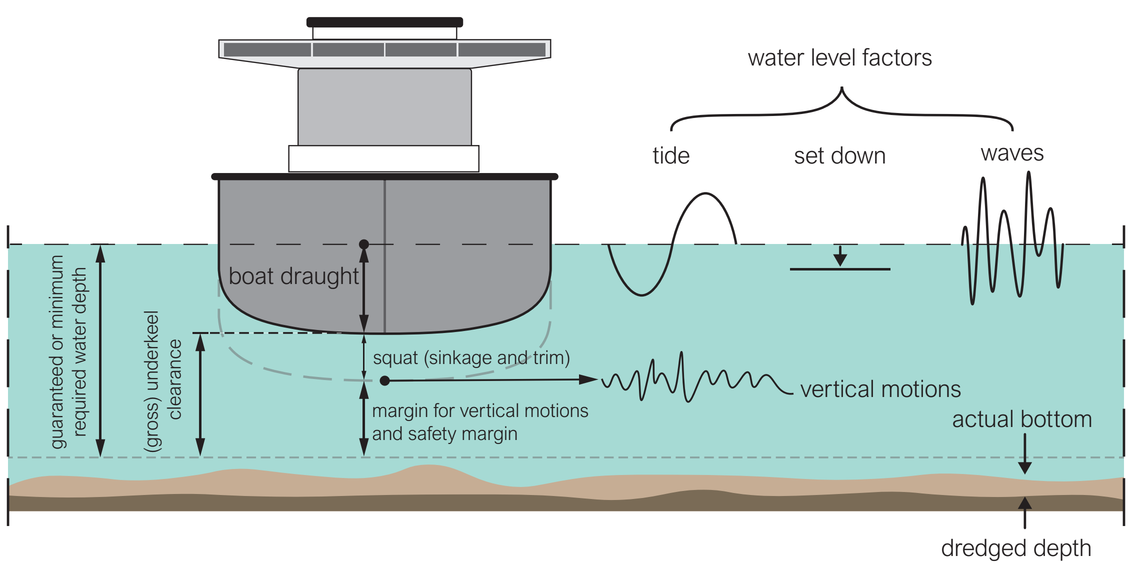


Figure 2.3: Factors influencing the required channel depth (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Given the cross-sectional dimensions of a channel, the water level depression grows as the ship's speed increases. It depends on the return current, the wave pattern around the ship and the trim. As the depression increases, the ship's squat (sinkage + trim) increases and the navigation margin with respect to the channel bed decreases. The main factors determining sinkage are:

- the ship's speed relative to the water;
- the configuration of the waterway, i.e. the water depth-to-draught ratio and the ratio of the channel width over the ship's beam.

We assume the sinkage to be equal to the maximum water level depression and trim to be absent. Then sinkage and water level depression are determined by the ship's speed and the blockage coefficient, that is the ratio of the cross-sectional areas of the ship, A_s, and the channel, A_c. Schijf (1949) gives an analytical calculation method for a rectangular ship sailing in a rectangular channel, assuming a horizontal water surface in each cross-section. In that case the sinkage is equal to the water level depression. We will describe this method in Chapter 4 of this part.

The parameter h_0/D_s is meant to determine the actual required depth, in which h_0 is the depth without navigation and D_s the draught of the reference vessel. It would therefore be better to take the water level depression z into account and use $(h_0 - z)/D_s$ as a parameter. The value of z, however, depends on many factors, such as the ship's speed, the blockage coefficient and the average water depth. In case of a trapezoidal profile it is even more complicated, as the water level depression also depends on the bank slope gradient and the actual channel width. Furthermore, the water level depression increases when sailing eccentrically in the channel.

All these factors make it hard to estimate the water level depression. In order to have a first impression, Figure 2.4 shows how z/h_0 varies with A_s/A_c when adopting Schijf's simplifications. Ships are assumed to sail with the so-called attainable speed, which is at about 90% of the limit speed, that is the maximum speed at which a specific ship can physically sail (further see Section 4.1.1).

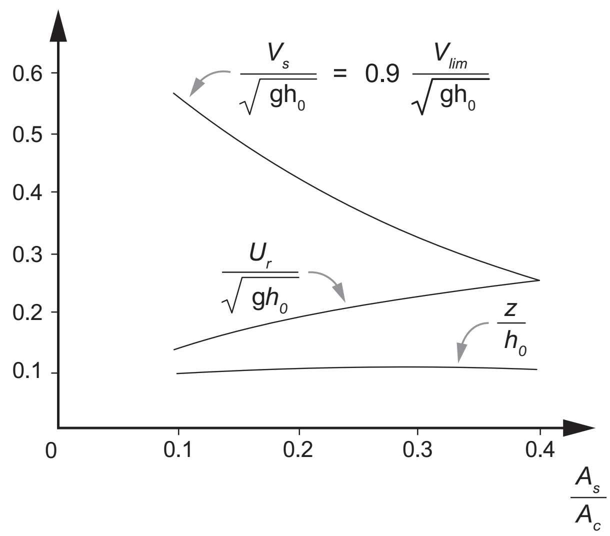


Figure 2.4: Return current velocity U_r, attainable velocity V_s (90% of the ship's limit speed V_{lim}) and water level depression at various blockage values (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 2.4 shows that with increasing blockage, the attainable speed reduces as the return current increases. The value of parameter z/h_0 is almost constant over the range of A_s/A_c values considered: $z/h_0 \approx 0.10$. This is half the value found if the ship would sail at its limit speed. Not only does sinkage increase rapidly at these high speeds, but the fuel consumption increases strongly and navigation gets difficult due to bottom and bank suction.

Good controllability of the ship requires sufficient depth (expressed in the h_0/D_s ratio). An indicator of controllability is the manoeuvring lane (or swept path), i.e. the width covered by the sailing ship, as sailing along a straight line is hardly possible. If the ship's course deviates from the intended one, the navigator will react by correcting the rudder or giving a power burst, depending on observation and reaction time. The sluggish response of a ship will lead to continual corrections and thus a fluctuating movement around the intended sailing line. While sailing, both the drift angle β (the angle between the longitudinal axis of the ship and the channel axis) and the rudder angle δ_r will continually change. Figure 2.5 gives an exaggerated example of this phenomenon.

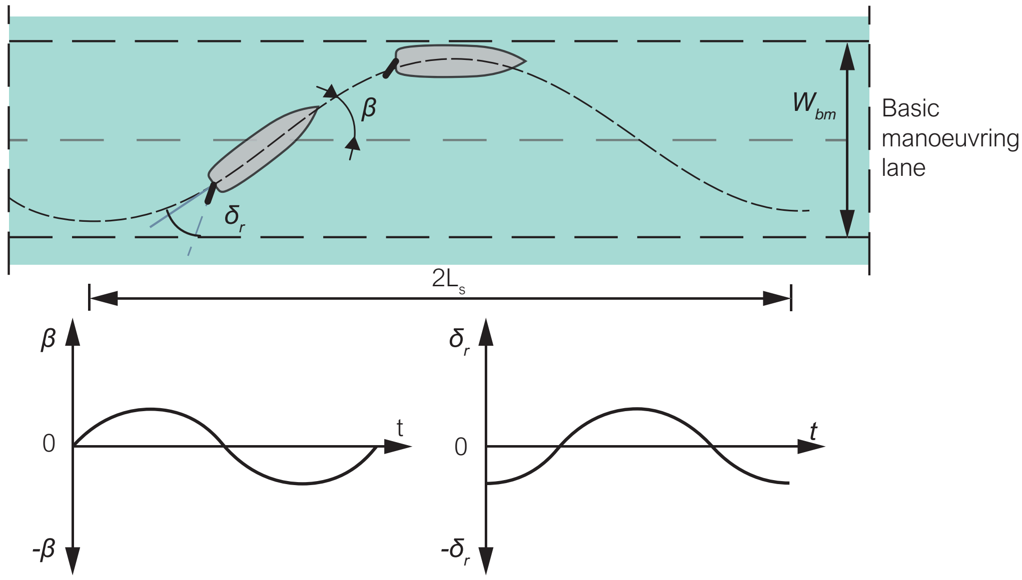


Figure 2.5: Manoeuvring lane in relation to drift and rudder angles (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The drift number is defined as W_{bm}/l, in which W_{bm} is the width of the swept path and l is the distance sailed in longitudinal direction between two consecutive extreme rudder deflections, hence half the wavelength of a sweep. The drift number appears to increase with the ship's length L_s.

A variety of tests has led to the conclusion that, for good controllability on waterways of Class IV and higher, the vertical navigation margin $h_0 - D_s$ should be at least 30-40% of the reference ship's draught. For push-tow units a navigation margin of 50% is advised. In obsolete smaller waterways (Class I to III) a ratio of 20% can still be found, but with ratios h_0/D_s smaller than 1.3, controllability rapidly decreases (Figure 2.6). The navigation margin has to be larger if wind waves can cause pitching and rolling, or in case of other possible disturbances, such as cross currents, translatory surges and especially wind abeam.

The maximum possible squat determines the depth at which grounding (e.g. touching of the bottom) is unlikely. In most cases, the draught of a ship is not constant over its entire length. The point of maximum draught is determined by a combination of sinkage and trim. Where overtaking is allowed, a larger depth is needed, because the overtaking vessel first sinks into the depression of the other vessel and then has to sail at full power in order to overcome the adverse water level gradient in the last phase of the manoeuvre. Therefore, overtaking may determine the design depth of a waterway.

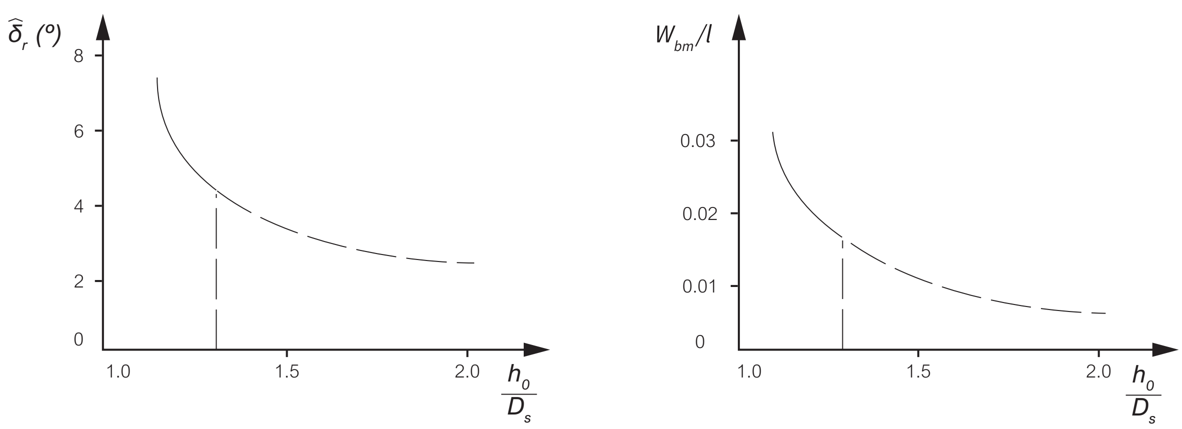


Figure 2.6: Maximum rudder angle and drift number as a function of the navigation margin (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Apart from the desired navigability, a certain minimum under keel clearance is needed to prevent bed scour caused by the propeller jet. A jet may cause sediment stirring, leading to bottom irregularities and even grounding of ships with small UKCs. When a ship has run aground, the helmsman will try to set the vessel free by forcefully trying to move the ship back and forth, in that way stirring even more sediment and causing more bottom disturbance. A vicious circle is looming: running aground, more propulsion, more bottom disturbance, more running aground, et cetera.

One might apply larger values of h_0/D_s than necessary for navigability. This is favourable from a nautical point of view, as higher speeds can be attained. On the other hand, larger UKCs appear to attract ships with larger draughts, rather than ships sailing at higher speeds, since a larger draught means more cargo, so more revenue.

2.1.2 Factors influencing the required waterway width

The required width of a waterway depends on the (expected) traffic intensity and the different types of (design) vessels, but also on the swept path (Figure 2.5). A newly constructed waterway will comprise at least two navigation lanes. It may even be necessary to include a third lane, a so-called overtaking lane, if there are large speed differences between ship types. If very high traffic intensities are expected, even a fourth lane may be needed. If effects such as wind and currents are taken into account, which are discussed in RVW (2020) and PIANC (2014c), implicitly a safe waterway has been designed.

The width of a navigation lane is determined by the characteristics of the design vessels, especially their beam. In waterways with more than one lane, the beam of the largest permitted design vessel is equally defining. The number of lanes in relation to the frequency of occurrence of a specific type of ship may justify the enforcement of a speed limitation for that type. One has to make sure that two of these design ships can safely pass by each other.

A number of issues determine the total required lane width. Below we will discuss navigating along the channel centreline and navigating eccentrically. The next subsections discuss a number of special cases (viz. bends, cross-sectional discontinuities, cross and longitudinal current and ship-ship interaction).

Navigating along the centreline

When a ship sails along the channel centreline, the swept path is an important determining factor for the lane width. The swept path depends on the length of the ship itself, and as the length/beam ratio of inland vessels is more or less constant ($L_s/B_s = 6$ to 8), the occupied width can be expressed in terms of the ship's beam. Apart from the oscillating path shown in Figure 2.5, the ship can have an instantaneous drift angle under the influence of winds, currents, et cetera. The largest width (W_{bm}) covered at any instant occurs when the drift angle (β) is maximum (see Figure 2.7):

$$W_{bm} = B_s \cdot \left(\frac{L_s}{B_s} \cdot \sin\beta + \cos\beta \right) \tag{2.1}$$

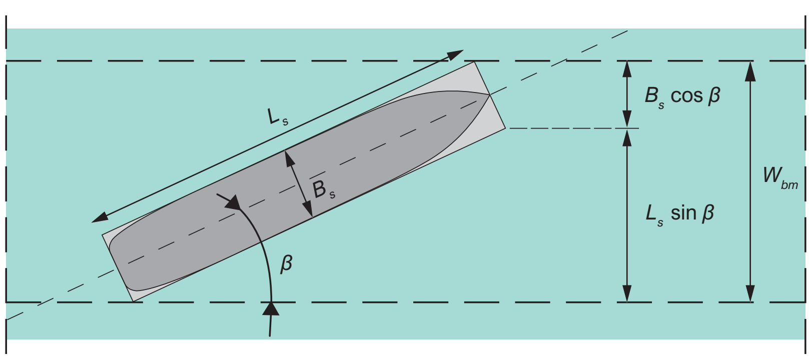


Figure 2.7: Largest width occupancy (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Required lane widths found in literature range between 1.2 and 1.4 times the ship's beam for conventional ships and between 1.1 and 1.3 for push-tow units. Tests in practice, however, gave larger values, e.g. 1.5 times the beam in case of push barge units. Empty ships in situations with wind abeam obviously need larger lane widths, just like ships with poor manoeuvrability. Furthermore, the required lane width will increase for small under keel clearances ($h_0/D_s \leq 1.3$), because of the poorer controllability.

Navigating eccentrically

When a ship is sailing along the channel centreline, the water level depression and the return current are symmetric about the ship axis. Hence the ship feels no lateral force or yaw moment. This is different, however, for ships sailing eccentrically, as the symmetry of the hydrodynamic effects is disturbed. Sailing eccentrically may occur in a multi-lane channel, when passing a bridge opening if this is not located in the channel centre, when encountering or overtaking other ships, et cetera.

Schijf's set-down calculation method does not include eccentricity. In order to include this, the value of the cross-sectional area A_c has to be replaced by the so-called imaginary wetted cross-sectional area A_{ci}:

$$\frac{A_{ci}}{A_c} = 1 - \mu \cdot \frac{y}{W_s - h_0 \cdot \cot \alpha} \tag{2.2}$$

in which W_s is the channel width at the undisturbed water line, y represents the eccentricity, i.e. the distance of the ship axis from the centreline, α the slope angle of the bank and μ a coefficient depending on the type of ship, equal to 0.4 - 0.64 for pushed convoys and 1.04 - 1.28 for motor barges (PIANC, 1987).

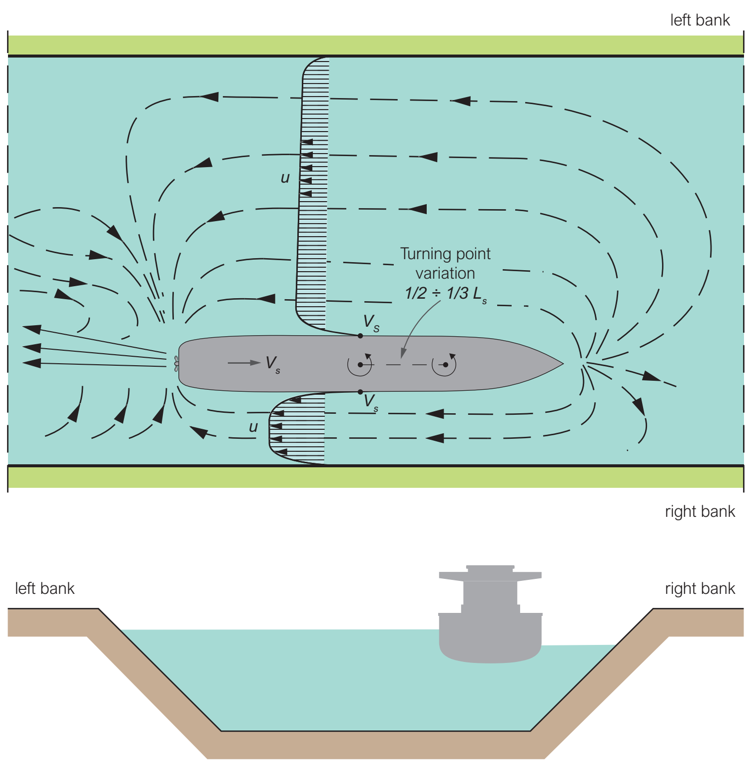


Figure 2.8: Current pattern induced by sailing eccentrically (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

A ship sailing eccentrically induces an asymmetric return current pattern. Yet, the discharge of the return current is about the same at either side of the ship. This means that return current velocities, hence the water level depression, are larger between the ship and the nearest bank (Figure 2.8). This creates a net force tending to push the ship to the near bank, as well as a moment tending to yaw the bow to the far bank (Figure 2.9). Bargemen call this phenomenon bank suction. Clearly, its magnitude depends on the distance between the ship and channel centreline, the speed of the ship, the blockage coefficient and the under keel clearance.

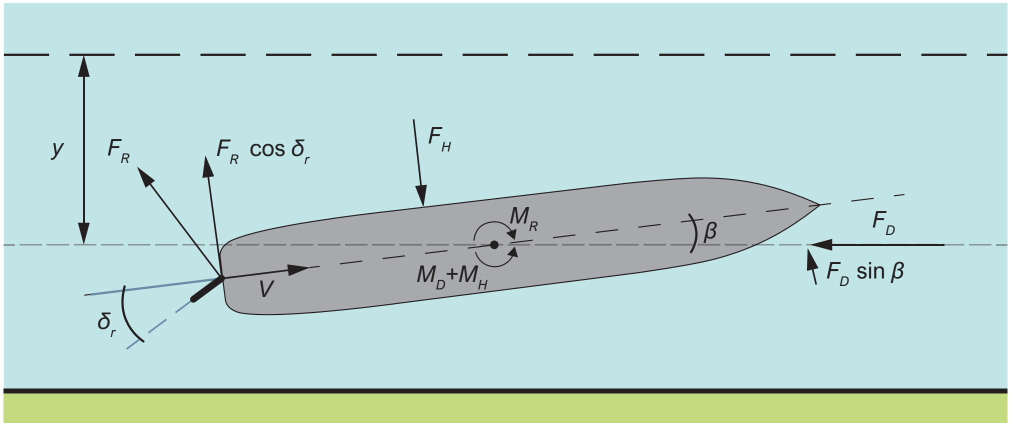


Figure 2.9: Forces on a ship sailing eccentrically (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Bank suction has to be compensated by changing the rudder angle and the propeller speed. In principle, this is an unstable operation. If the rudder angle can be kept small, it leads to a course away from the bank, but if the rudder reaches its maximum deflection it may lead to a loss of controllability, with the stern hitting the bank. In the controlled situation, the navigator will try to bring the ship back to the intended course. Due to the ship's inertia, this leads to a fluctuating sailing course, like navigation along the centreline of the waterway (Figure 2.5), but now with non-zero mean rudder and drift angles (Figure 2.10). In principle, this fluctuating course would require an additional lane width compared to the situation in which the ship would sail exactly along the channel axis, but the present rules for the canal width already take this into account.

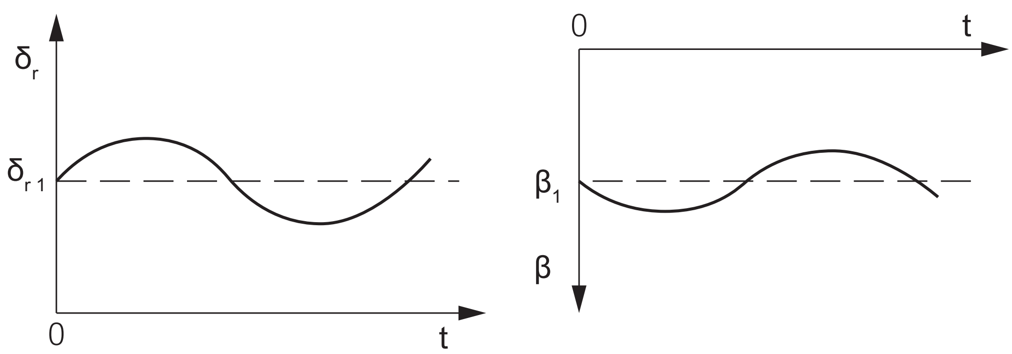


Figure 2.10: Rudder angle and drift angle when sailing eccentrically (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

To keep the ship in balance, both the transverse force as well as the moment have to be counterbalanced. The rudder alone is not capable of doing so, because of its fixed position behind the ship. The rudder force is adaptable by changing the rudder deflection and the number of rotations of the propeller. This balance can be achieved by not only adjusting a rudder angle, but also by giving the ship a drift angle (β) with respect to the canal centreline, resulting in an extra perpendicular counterforce at the bow. The now adjusted rudder angle is called the equilibrium rudder angle. Approximate values for the mean rudder angle are 3° for a blockage coefficient $k =$ 0.11 and 15° for a blockage coefficient $k = 0.28$, both at moderate speeds (Kwik, 1992).

The situation for push-tow units sailing eccentrically may be completely different, depending on the water depth and the form of the underwater bow. Contrary to conventional ships, push barges usually have a rather blunt bow. Consequently, the water displaced by it flows in the direction of the least resistance. In case of a limited water depth, most water will flow slantwise underneath the barge towards the channel centreline. Thus, at the front side of the ship, the water level at the side of the nearest bank will be higher than at the side of the channel centre. Steering towards the bank is necessary to keep the unit from yawing away from the bank. Consequently, the position of a push barge unit sailing eccentrically will be contrary to that of a conventional ship (Figure 2.11).

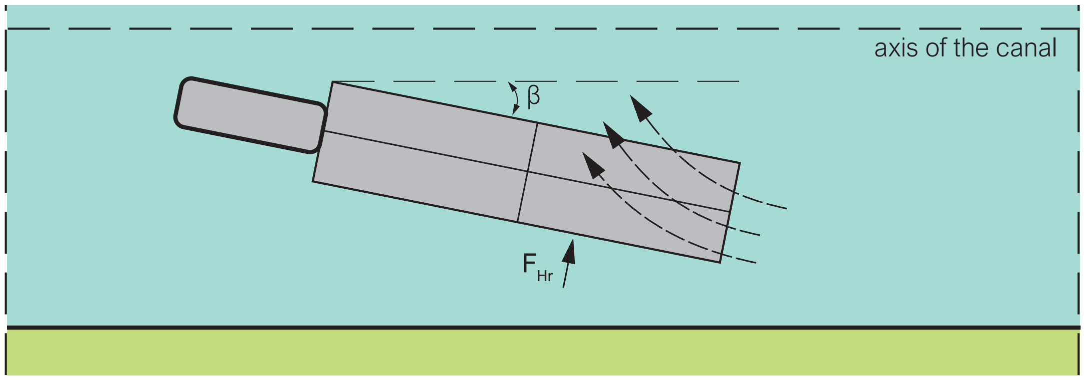


Figure 2.11: Pushed convoy sailing eccentrically (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

In deeper channels the displaced water will be less forced to flow slantwise. The position of the push barge unit then will become less directed toward the bank, as was proven in model tests. For a water depth of two times the ship's draught, the unit's behaviour will be consistent with that of a conventional ship. Such a large water depth, however, is rare in inland waterways.

2.1.3 Navigation in bends

When a vessel sails through a curved section of the fairway, the ship's centreline will deviate from the tangent to the bend curved path. The centreline will point towards the inner bend. An extra drift angle is required to counteract the centrifugal force. The drift angle is smaller if the vessel speed or the depth are smaller, or if the bend radius is larger. The draught and wind forces are of also relavant. The latter is especially important to realise in monsoon and cyclone areas.

It is difficult to determine a proper course when passing through a bend. The navigator normally orientates on the channel banks, but in a bend this becomes problematic.

While sailing through the outer bend, the outer bank will be skirted as closely as possible. To avoid running aground on the bank, ships are usually headed slightly towards the inside bank and they sail at a slightly higher speed. Thus at the bend exit, ships may have a higher speed than otherwise desirable.

When sailing through the inner bend, the ship is directed towards the inner bank (Figure 2.12). Though this serves to make navigation easier, the disadvantage is that a large rudder angle is needed for changing course and for resisting bank suction, which is enhanced by the shallower water depth. Therefore ship speed is usually reduced here.

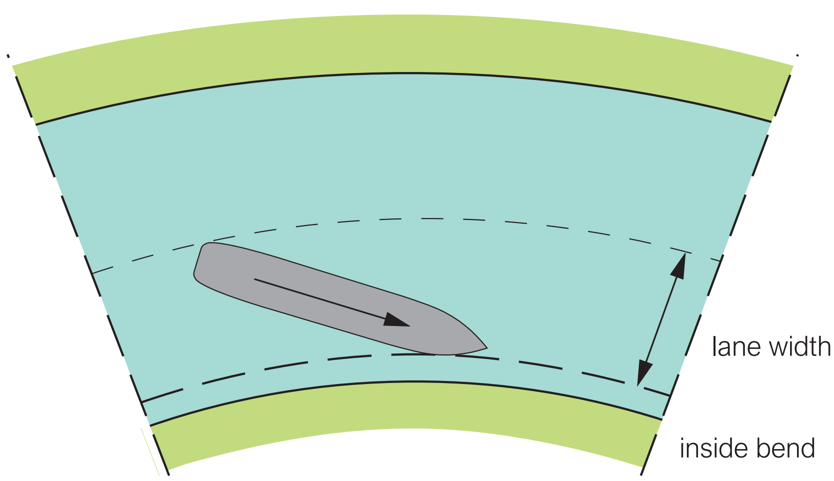


Figure 2.12: Navigation inside bend (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The most difficult part of passing through a bend is the transition from a straight canal section to the bend itself. The position of the ship has to change most drastically here and the navigator will find it difficult to fix the course with respect to the banks. Figure 2.13 illustrates that large fluctuations around a certain drift angle (here 0.5°) can be the result.

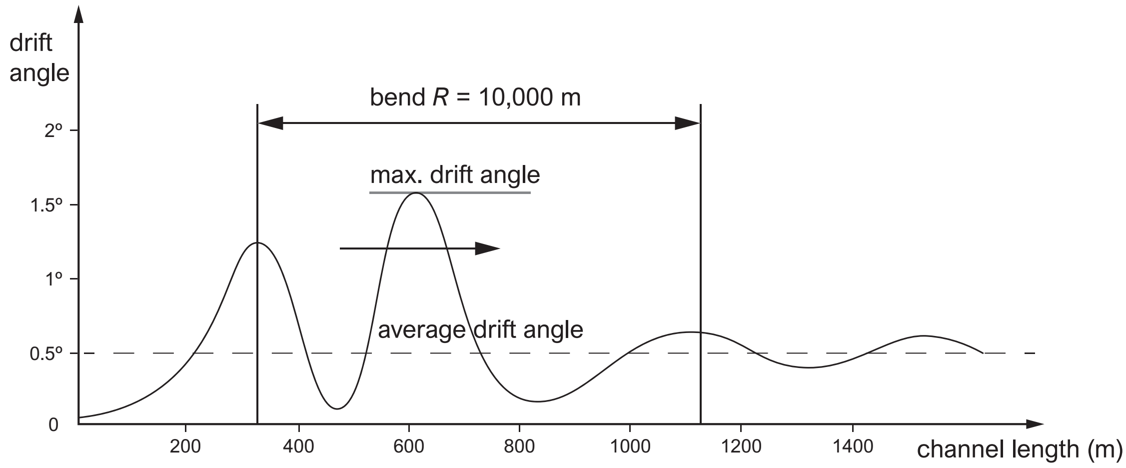


Figure 2.13: Example of the variation of a ship's drift angle when passing through a bend (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 2.14 gives the drift angle β as a function of the bend radius R and the ship's speed. It shows the average and maximum drift angle as obtained from tests (Schäle, 1968c,d,b,a) with push barge units of 160 m long and 9.5 m beam.

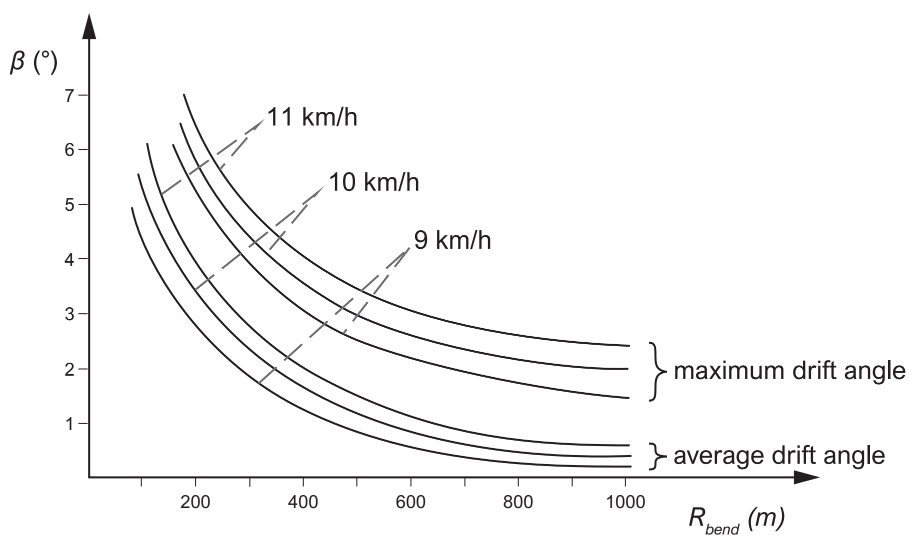


Figure 2.14: Drift angle as a function of bend radius and navigation (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Especially in sharp bends the drift angle may necessitate local widening of the fairway, in order to have the same navigation safety as in a straight channel. Design guidelines specify the additional width in bends as a function of the bend radius and the vessel length.

The above applies to stagnant as well as flowing water. Yet, there are differences. Sailing along with the current requires a larger lane width because of the smaller manoeuvrability (less pressure on the rudder). Sailing against the current requires a smaller drift angle and reduces the hydraulic effects on the vessel's hull such as bank suction.

2.1.4 Cross-sectional discontinuities

Discontinuities in the channel profile require a timely response of the navigator, and therefore good visibility. A minimum visibility of four times the length of the ship is required for commercial navigation, given the long stopping distances. Navigators will slow down if the visibility is less. Recreational traffic requires a visibility of at least 100 m. Nevertheless, navigation is disturbed at an abrupt narrowing or widening of the channel cross-section.

Cross-section widening

Abrupt channel widenings may be found at ports entrances, diversions, confluences, islands and receding loading and unloading quays (Figure 2.15).

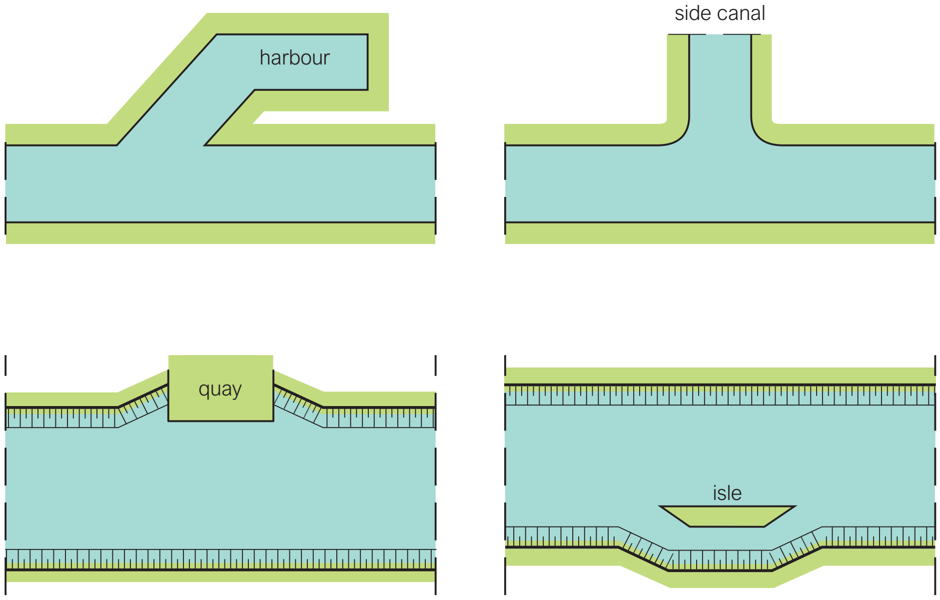


Figure 2.15: Examples of abrupt channel widening (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

When a ship approaches such a channel expansion, the front wave will decrease at the side of the expansion. This causes a decrease of the pressure at the bow of the ship at the side of the expansion. Consequently, the ship will tend to steer towards the expansion. A little further down another force comes into play: water flowing from the side of the expansion partly fills up the water level depression, forcing the ship away from the expansion. The passing process is illustrated in Figure 2.16.

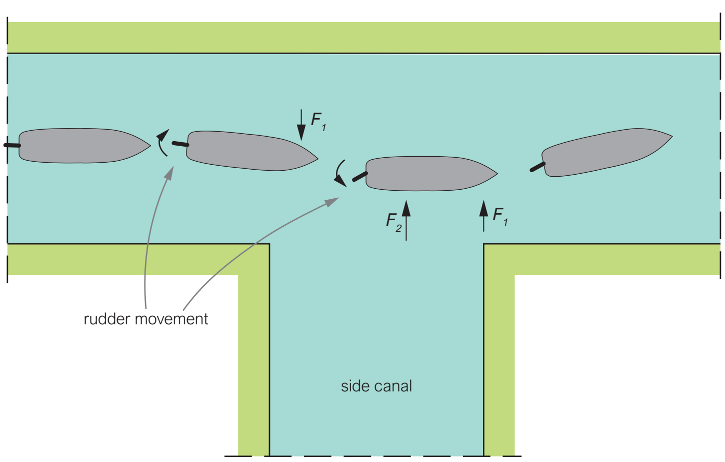


Figure 2.16: Passage of a side canal (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

If the width of the side canal in the situation of Figure 2.16 is of the same order of magnitude as that of the main channel, the process described above will have a significant impact on the ship's manoeuvring. If the side canal is much narrower than the main channel, manoeuvring will hardly be influenced.

Cross-section narrowing

A constriction of a cross-section is to be expected in case of bridge piers, or if a wharf extends into the channel profile, see Figure 2.17.

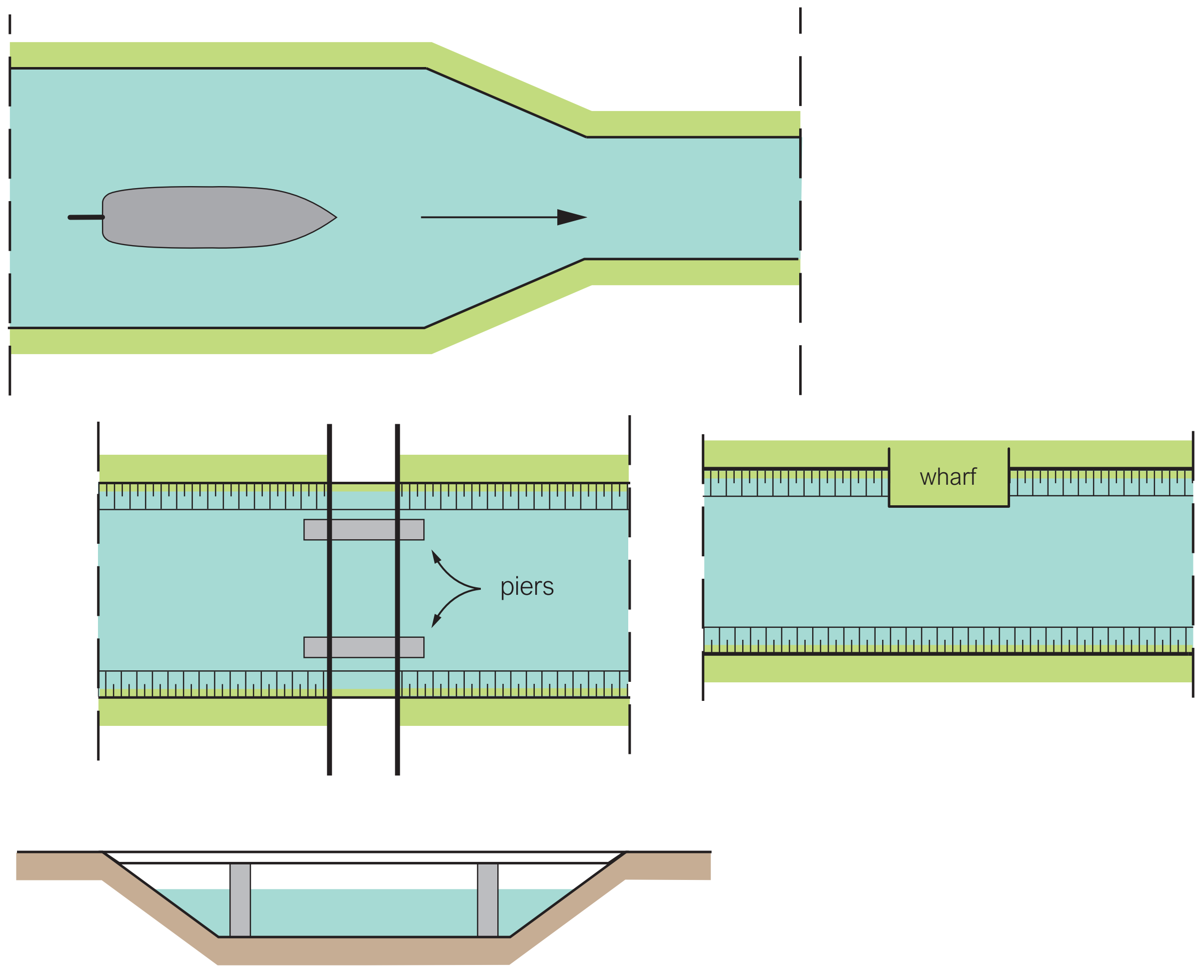


Figure 2.17: Examples of channel constrictions (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

A ship sailing in the centreline of an abruptly narrowing channel will cause a stronger return current, hence a deeper water level depression, so its squat will increase. If it sails eccentrically, bank suction will increase. Furthermore, the ship's speed will decrease, which induces translation waves at the discontinuity.

Passing a narrow section like a bridge requires extra force on the rudder. This can be achieved by increasing the propeller speed. Yet, the navigator needs to keep extra rudder capacity available, for instance in case of strong bank suction. In the narrow part he will therefore reduce the speed in order to have sufficient power available in critical situations.

2.1.5 Cross and longitudinal current

Another type of disturbance are longitudinal and cross-currents. A longitudinal current influences the navigation speed and the ship's manoeuvring. Concentrated cross-currents, like those caused by lateral water intakes or outfalls, may form a big hindrance to navigation.

Cross-currents exert a transverse force and a moment on the ship, causing it to sway and yaw, respectively. To counterbalance these effects the navigator has to set the ship under an angle with the straight course (Figure 2.18). In the case of an elongated cross-current field, an equilibrium drift angle will establish, depending on the cross-current velocity and the ship's speed. Once the equilibrium state has established, the rudder can be placed into the middle position.

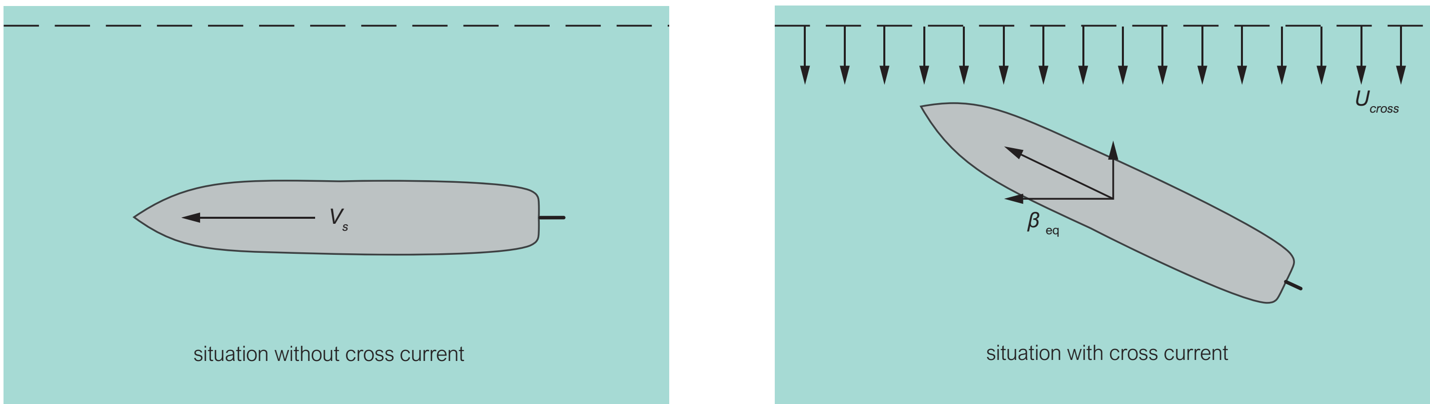


Figure 2.18: Navigation with a cross-current (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The degree of hindrance to the shipping traffic depends on:

- the field over which the cross-current is active as compared with the length of the ship;
- the average cross-current velocity;
- the vertical position of the intake or outfall;
- cross-current on one side or both sides of the channel;
- distance of the sailing track to the bank, and
- the ratio of the ship speed and the cross-current velocity.

In the case of a concentrated outfall, the maximum allowable cross-current velocity depends on the cross-sectional area of the orifice. For small orifices higher cross-current velocities can be allowed than for large ones. Figure 2.19 shows the maximum cross-current velocity as a function of the orifice perimeter. It indicates in which cases further research is needed because the standard allowable velocity is exceeded. For large orifice perimeters a current velocity of 0.3 m/s appears to be acceptable. Given the navigation speeds normally encountered in shipping channels, such a velocity would lead to an extra width requirement of the order of magnitude of one ship beam. The Dutch Waterway Guidelines (RVW, 2020) presents a method for cross-currents up to 2.5 m/s.

In the case of water intake, the hindrance of a deviant current pattern is much smaller and allowable current velocities at the intake can be 1.5 times higher than for outlets. Research carried out by Meyer and Schaele (1985) found increased values for inlet velocities:

- 2 m/s for the Rhine and its tributaries
- 1.5 m/s for rivers of standard V Class
- 0.6 m/s for rivers of standard IV Class.

In channels with longitudinal currents, ships sailing upstream are faced with a considerable loss of travelling time, but their manoeuvrability is relatively good. When ships are sailing downstream at full force, their speed is relatively high, which makes it difficult to slow down within a short distance in case of unexpected traffic situations. When sailing downstream at a low speed, however, there is little pressure on the rudder, which reduces manoeuvrability. High current velocities therefore have a negative impact on traffic safety at small waterways. However, taking into account the situation near bridges, sharp bends, manoeuvring places etc., a longitudinale current (averaged over the cross-section) of 0.5 m/s is generally considered allowable.

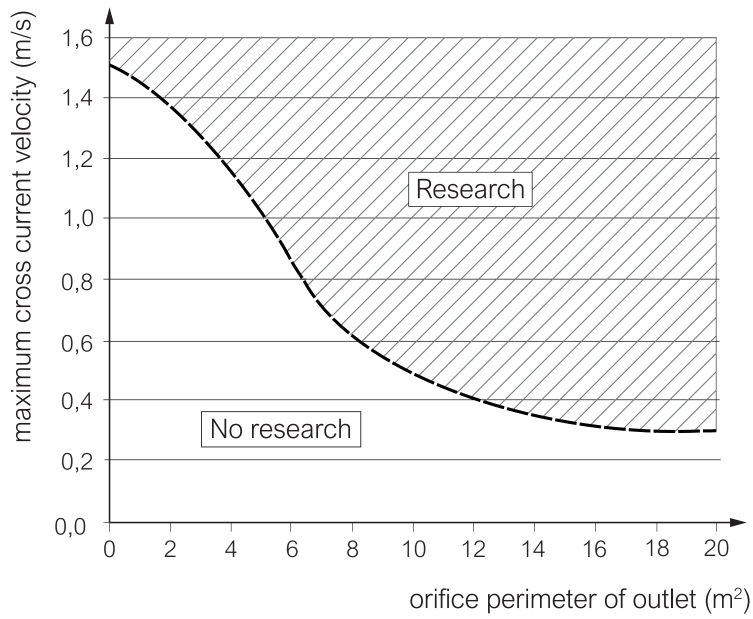


Figure 2.19: Maximum cross current velocity as a function of the orifice parameter (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

2.1.6 Ship-ship interaction

This section discusses the phenomena related to ship encounters and overtakings. Section 4.4.5 deals with the hydrodynamics in case of overtaking.

Encountering manoeuvre

At the start of an encounter the ships push each other aside because of the water movement around the bow. Laden ships therefore approach each other as close as possible when starting the encountering manoeuvre. The smaller of the two will reduce its speed most, since it faces a relatively larger narrowing of the cross-sectional area available, due to the blockage by the midships section of the larger ship and the associated water level depression. Just before passing, the navigator will temporarily reduce the propeller speed, in order to have sufficient power in case of hazardous situations.

When the bows are opposite to each other (Figure 2.20, Situation 1) the bows tend to yaw away, but bank suction opposes this tendency. When the ships are next to each other (Figure 2.20, Situation 2), their opposing return currents partly or completely balance out. The water level depression between the two ships will therefore be smaller than between ship and bank (Figure 2.21). The difference in hydrostatic pressure forces the ships to sway away from each other. To what extent this will happen depends on the distance between the two passing ships.

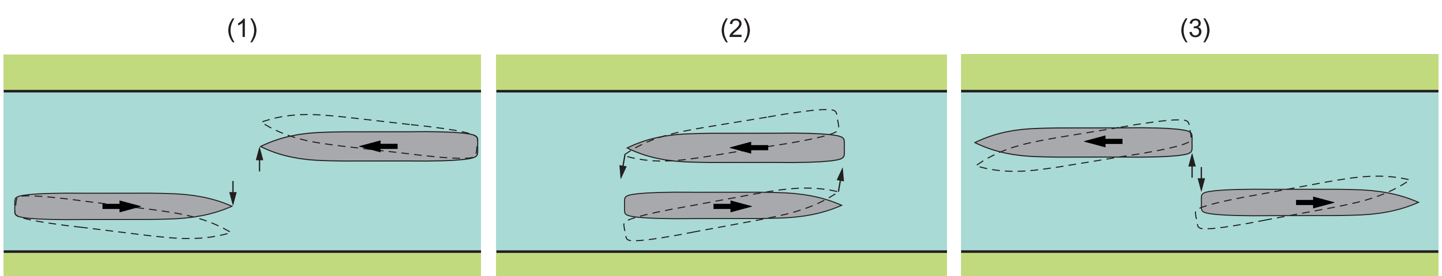


Figure 2.20: Phenomena when two ships encounter in a channel (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

When the bows approach each other's stern (Figure 2.20, Situation 2), the bows yaw toward the centreline and the bank suction tends to reinforce this movement. Finally, when the sterns are opposite to each other (Figure 2.20, Situation 3), the sterns yaw toward the centreline at sterns but bank suction opposes this tendency.

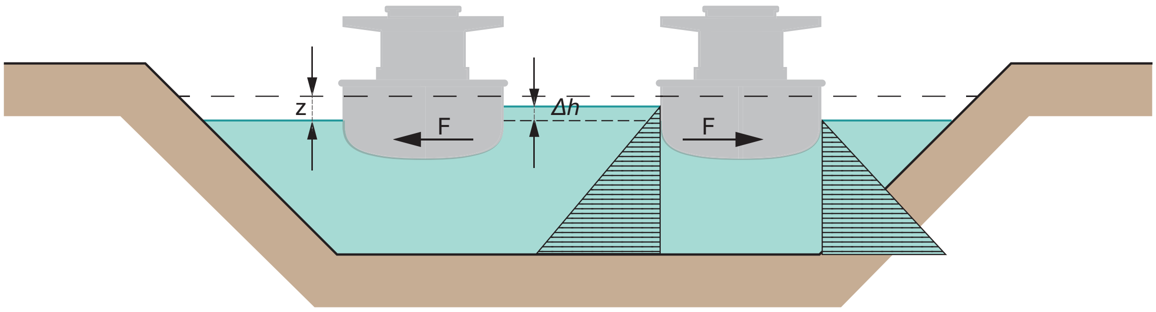


Figure 2.21: Lateral forces on encountering ships (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

So, apart from the mutual influence of the ships, bank suction plays a significant role. This is especially true for two types of vessels: coasters and pushed convoys. Coasters experience more bank suction because of their relatively low L_s/B_s ratio. The bow of pushed convoys is normally directed towards the bank when sailing outside the axis (cf. Figure 2.11). In an encountering manoeuvre they therefore run an even greater risk of grounding on the bank. Furthermore, the bank suction will be larger, because of the larger width of pushed convoys. Moreover, pushed convoys are less manoeuvrable than conventional motor vessels, because of their larger size, mass and inertia.

Two dangerous situations thus occur in an encountering manoeuvre. The first is the moment at which the two ships begin to feel each other's influence. They run the risk of yawing away from each other and grounding on the bank (Figure 2.22, situation a). The second situation occurs when too much rudder force is used to avoid grounding on the bank. This involves the risk of collision with a following ship or hitting the opposite bank (Figure 2.22, situation b).

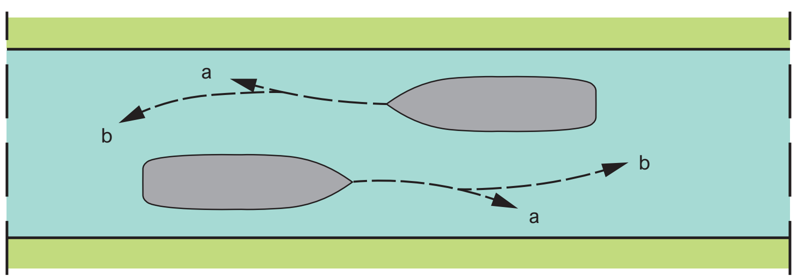


Figure 2.22: Dangerous situations during an encounter (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

For experienced helmsmen an encountering manoeuvre in fact only gives problems in relatively narrow waterways. Even though the forces exerted on the ships can be significantly larger than in an overtaking manoeuvre, the effect is limited because of the restricted duration of an encounter. For standard inland vessels this duration is between 10 and 30 seconds. For push convoys this may increase to 1.0 to 1.5 minutes.

Overtaking manoeuvre

At the start of the overtaking manoeuvre, the bow of the overtaking ship will be pulled towards the stern of the ship to be overtaken. Then the overtaking ship enters the area of water-level depression of the ship to be overtaken and will get drawn in. Due to this extra return current at the bow, a small change of the ship's course leads to a large change of the yawing moment.

When the two ships sail directly alongside the return current and the water-level depression of the two ships will reinforce each other. Therefore the water level will be lower between the two ships than between ship and bank.

The ships will encounter more resistance, and as the overtaking manoeuvre proceeds, they will be swaying towards each other due to the difference in hydrostatic pressure (Figure 2.23). If the ships are drawn against each other, they effectively form one ship and will inevitably lose control. Both ships will therefore try avoid getting too close to each other, but they also have to make sure that they do not ground due to bank suction.

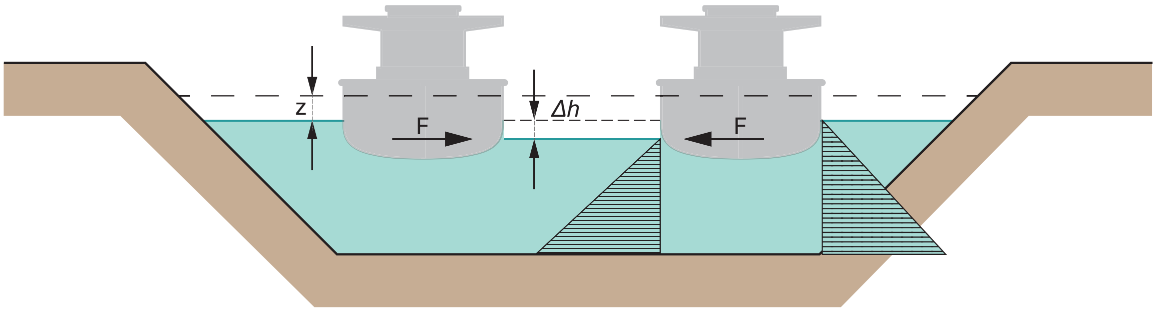


Figure 2.23: Hydrostatic pressure when ships overtake each other (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

In the last phase of the manoeuvre, the overtaking ship has to overcome the adverse water level gradient associated with the other ship's water level depression. The same situation as in the beginning occurs, only this phase takes much longer.

Various circumstances may make it impossible to complete the overtaking manoeuvre. For instance, the overtaking ship may have insufficient power to overcome the extra resistance. In that case the overtaking manoeuvre can be completed if the ship to be overtaken strongly reduces its speed and the overtaking ships sails at an adjusted speed in order not to be drawn against the other ship. Speed reduction, however, requires caution because the rudder pressure has to stay high enough for manoeuvrability. Practically speaking, overtaking is only feasible if the speed difference between the two ships is more than 5 km/h.

Section 4.4.5 discusses hydrodynamic phenomena associated with overtaking manoeuvres in more detail. Section 4.6 gives an examples of numerical model computations of these hydrodynamics.

Stopping distance

Another form of ship-ship interaction occurs when a ship unexpectedly stops, for instance because it has machine problems, it runs aground, or to avoid a collision. Note that it can take several minutes to bring a large ship to a stop and that the stopping distance can be several times the ship's length. The spacing between the ships must therefore be sufficient to enable the next ship to safely stop before reaching the vessel ahead.

So far, little is known about the stopping distance of a ship in a shallow channel. The stopping distance in a shallow channel is presumably a function of the blockage factor, ship speed, ship displacement and ship block coefficient. It is likely to be smaller than in deep open water due to the increased resistance caused by the enhanced return current. On the other hand, in a confined channel there will be a larger added mass of water giving the ship extra momentum. This will increase the time and distance needed for stopping.

To meet safety requirements the gap between successive ships must not be smaller than the stopping distance. This determines the maximum traffic density (the maximum number of ships per unit channel length) on a single-lane channel. In all this, the possibility of casting the anchor in an emergency has not been taken into account.

Binnenvaart Politie Reglement (BPR) and Rijnvaart Politie Reglement (RPR) mention stopping distances related to the vessel length. In general, the stopping distance is at least about 2 to 3 times the vessel length:

$$L_{st} > (2 \div 3)L_s \tag{2.3}$$

where L_{st} is the stopping distance in metres.

2.2 Inland waterways

2.2.1 Design standards for the waterway cross-section

Given the criteria for the waterway depth and width discussed in the previous section, the required dimensions of a waterway cross-section can be derived. Internationally, PIANC presents the design guidelines in use in different countries over the world (PIANC, 2019a). Recently, PIANC started a new working group (WG179) on how to deal with new ship types. In the Netherlands, Rijkswaterstaat developed the Richtlijnen Vaarwegen (RVW, 2020). Figure 2.24 summarises the Dutch guidelines (excluding the additional width required for wind effects) for the dimensions of single-lane and two-lane channels. It shows that the aforementioned width standards apply at the keel level of a non-moving ship. In case of a trapezoidal or combined rectangular-trapezoidal profile not only $h_0/D_{\text{s, loaded}}$, $h_0/D_{\text{s, unloaded}}$, but also W_d/B_s will decrease as the ship's speed increases, because of the larger water-level depression. The decrease in available width appears to depend strongly on the bank slope. For a slope of 1:4 and a water-level depression of for instance 0.40 m, the decrease in the plane of the keel is 2 x 4 x 0.40 = 3.20 m.

In general, four canal profiles for commercial traffic are considered:

- Intensity profile
- Preferred profile with 2 traffic lanes
- Reduced profile with 2 traffic lanes
- One way profile

These profiles are related to the traffic intensity. For waterways with more than 30,000 vessels/year the intensity profile should be used. A normal intensity of 15,000 to 30,000 vessels/year requires the preferred profile, a low intensity of 5,000 to 15,000 vessels/year requires a preferred profile, allowing locally over short distances a reduced profile. In case of a very low intensity (less than 5,000 vessels/year) a reduced profile is possible with locally a one-way profile.

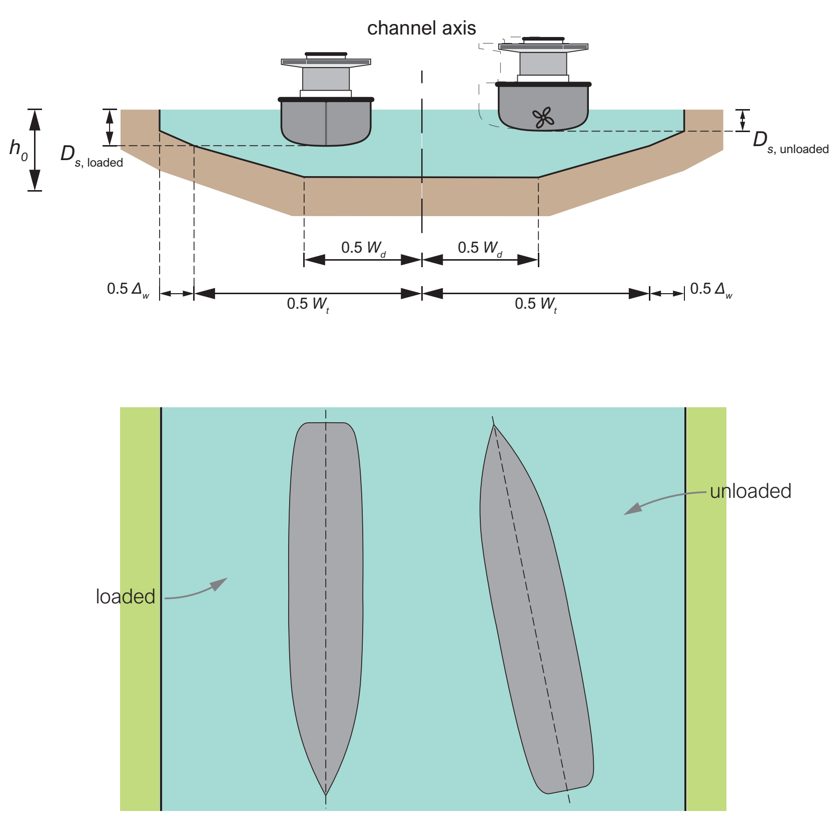


Figure 2.24: Standard for two way cross-section (reworked from RVW, 2020, by TU Delft – Ports and Waterways licenced under CC BY-NC-SA 4.0).

Table 2.1 shows the requirements for the different profiles, except for the intensity profile, which requires additional investigations.

Profile	W_d/B_s [-]	W_t/B_s [-]	h_0/D_s [-]
Preferred	2	4	1.4
Reduced	2	3	1.3
One way	1	2	1.3

Table 2.1: Normative values for the width at the bottom, the width at keel level and the water depth.

The ratio h_0/D_s determines the manoeuvrability: the larger this parameter, the smaller the average swept path. The overtaking manoeuvre is the limiting factor, because of the higher speed, hence the largest water level depression and squat. A value of $h_0/D_s \geq 1.4$ is advised for high-intensity navigation channels of Class IV and higher. For shorter access channels or channels with a low traffic intensity of a lower class (Class I to III, frequently with a reduced or one-way profile) $h_0/D_s = 1.3$ is sufficient. The ratios W_d/B_s and W_t/B_s are related to the maximum traffic intensity, given the frequency of occurrence of vessels of different types.

In addition to these normative values, the width at keel level of an unloaded vessel has to be equal to the width at keel level of a loaded vessel plus an additional width Δw for cross wind. Obviously, the channel profile is symmetrical. For the preferred profile the extra wind width is about 0.05 L_s at inland locations and about 0.10 L_s in coastal areas. Loaded vessels experience less hinder of cross wind, and therefore have no extra wind width requirement. Only vessels with a large windage, such as container vessels, experience wind hinder on inland waterways.

Apart from the depth parameter, the blockage ratio A_c/A_s is particularly important for the maximum attainable navigation speed. The Dutch guidelines, however, do not include a design value for it. Being strongly related to the navigation speed, it is a indicator of the nautical quality of the cross-section chosen. In general, the blockage ratio for a preferred profile is about 7, for a reduced profile 5 and for a one-way profile 3.5.

The maximum navigation speed in a trapezoidal channel is defined as 0.9 times the physical limit speed V_{lim} according to Schijf's method (see Section 4.1.1). The maximum speed in a rectangular channel is significantly higher than in a trapezoidal one, as we will show below.

Ship speed in a rectangular and trapezoidal channel profile

For a trapezoidal profile with slope 1:m, the width at water level is given by (also see Figure 2.25):

$$W_s = \frac{A_c}{h_0} + m \cdot h_0 = \frac{B_s}{k\,(h_0/D_s)} + m \cdot h_0 \tag{2.4}$$

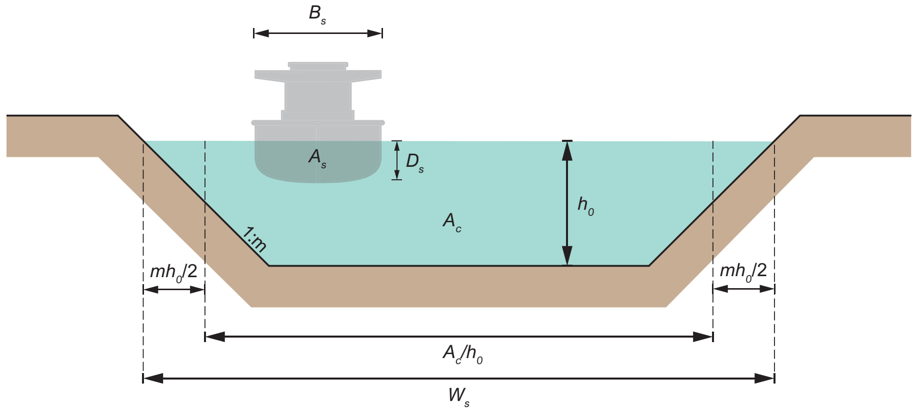


Figure 2.25: Trapezoidal canal profile (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The underwater dimensions of the standard design vessel ($B_s \cdot D_s$), the bank slope and the normative standards for the waterway depth (h_0/D_s) and the blockage coefficient ($k = A_s/A_c$) determine the required trapezoidal profile dimensions, hence the (maximum) speed of 0.9 $\cdot V_{lim}$.

Given the vessel speed, the return current and the water-level depression increase from a rectangular profile via a combined rectangular-trapezoidal profile to a trapezoidal profile. This difference is not only associated with the difference in blockage coefficient, but most of all with the difference in width at the undisturbed water level. This means that a higher navigation speed can be reached in a rectangular profile than in a trapezoidal profile of the same depth and cross-sectional area. In the upper panel of Figure 2.26 the width at the water surface is kept the same, in the lower panel the undisturbed water depth is the same. The water level depression increases with the Froude number. For a given blockage coefficient, it can be shown (see Section 4.1.1) that this number has to be based on the mean depth, irrespective of the cross-sectional shape. So, for a ship sailing at the limit speed:

$$Fr_{lim} = \frac{V_{lim}}{\sqrt{g\bar{h}}} = \frac{V_{lim}}{\sqrt{g \cdot (A_c/W_s)}} \tag{2.5}$$

In the situation of the upper panel of Figure 2.26 the Froude number according to Equation 2.5 is the same in either case. Therefore, the maximum navigation speed will also be the same in either case. In the situation of the lower panel, however, the Froude numbers are different. Hence the maximum navigation speed is significantly higher in the case of the rectangular channel:

$$V_{\text{s, rectangular}} = \frac{\sqrt{g \cdot h_0}}{\sqrt{g \cdot (A_c/W_s)}} \cdot V_{\text{s, trapezoidal}} = \sqrt{\frac{W_s}{\overline{W}}} \cdot V_{\text{s, trapezoidal}} \tag{2.6}$$

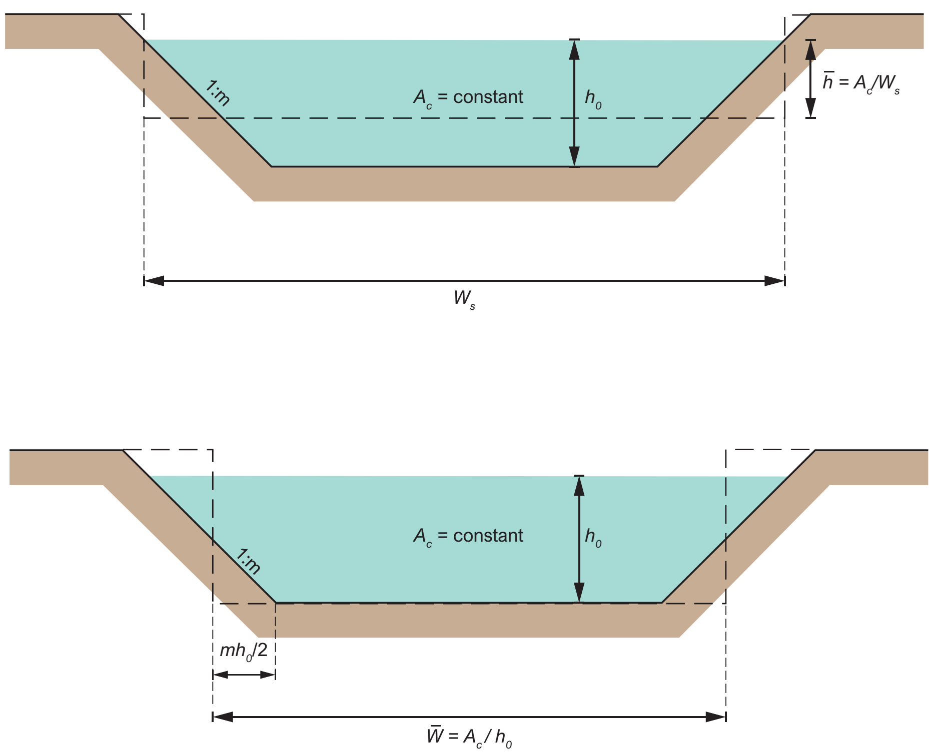


Figure 2.26: Comparison between trapezoidal and rectangular profile (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Rivers

The minimum navigable profile for commercial shipping on rivers is rectangular, with a navigable width $\overline{W}$ and a navigable depth h_0 (Figure 2.27). The width $\overline{W}$ equals the width W_t for canals plus an extra width for cross wind and longitudinal current. The extra width for longitudinal current is only required if the current velocity exceeds 0.5 m/s; it varies between 0.5 m and 4.5 m, depending on the current velocity and the CEMT class.

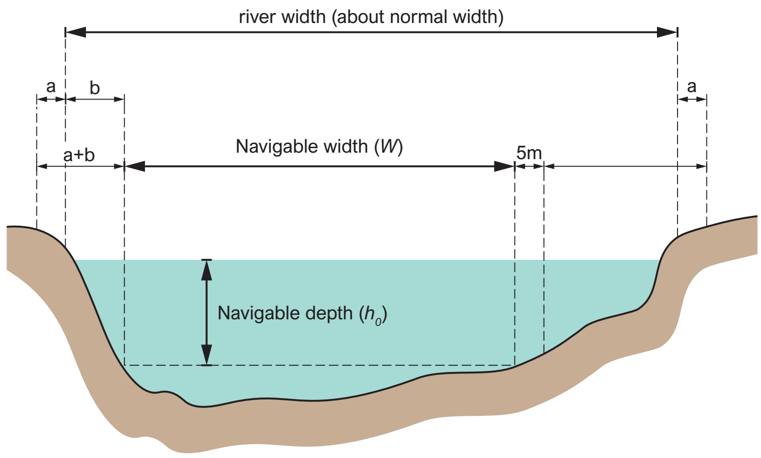


Figure 2.27: Definition of the navigable channel in a river (reworked from RVW, 2020, by TU Delft – Ports and Waterways licenced under CC BY-NC-SA 4.0).

For the river Waal, Upper Rhine and Lower Rhine in the Netherlands a minimum depth of 2.8 m has been defined as the Agreed Low Waterlevel (ALW); that is the water level that is exceeded 95% of the time. For the river IJssel this is 2.5 m. This has been laid down in an international agreement under the auspices of the Central Commission for the Navigation of the Rhine (CCNR). As the water depth varies with the discharge, the h_0/D_s ratio will often be less than 1.4, which may result in an under keel clearance of 0.3 m or less.

2.2.2 Cross-section in bends

A basic assumption in the design of a channel bend is that in the preferred cross-section two standard vessels (laden or unladen) should be able to encounter safely and smoothly. In a reduced profile encountering should be possible with speed reduction.

The required lane width for a ship passing through a bend is larger than in a straight reach (see Section 2.1.3). This is due to the ship's oblique position with respect to the canal centreline. An extra drift angle is required to counteract the centrifugal force when sailing in the bend. The oblique position is even reinforced, as navigators have difficulty fixing the course properly while passing bends. When designing a canal profile one must consider:

- that the maximum drift angle is only reached after prolonged rotation through a bend of constant radius; in a sharp bend the maximum drift angle may be reached faster; and
- a vessel sailing against the current generally has less ground speed, hence a smaller centrifugal force to compensate, so a smaller drift angle; consequently, when encountering another vessel sailing with the current, such a vessel will need less room than allowed for, in favour of the downstream vessel which needs extra space; moreover, a vessel sailing against the current can stop easily and close to the bank without any risk, in order to let pass a ship sailing downstream that occupies too much width.

For a preferred profile the bend radius should be at least 6 times the length of the design vessel (RVW, 2020). The extra width required follows from (see Figure 2.28):

$$\Delta B = \Delta B_{\text{loaded}} + \Delta B_{\text{unloaded}} = (\alpha_1 + \alpha_2)\frac{L_s^2}{R_{\text{bend}}} \tag{2.7}$$

to be added in the inner bend. Values for α_1 vary between 0.25 and 0.45, and for α_2 between 0.35 and 0.95.

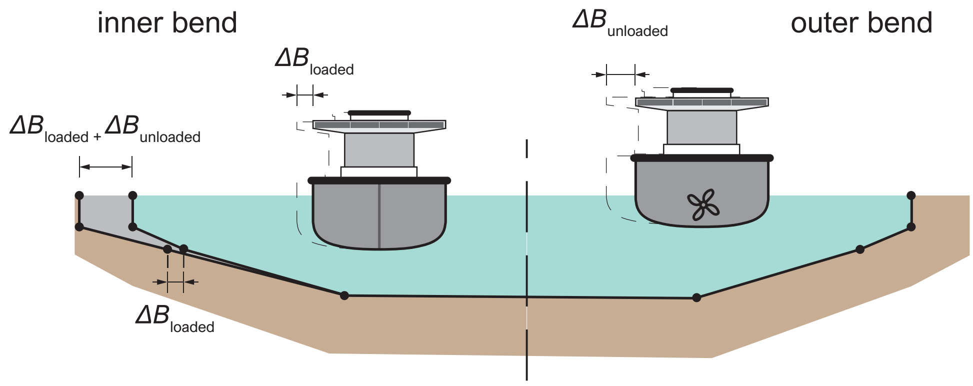


Figure 2.28: Extra width in the inner bend (reworked from RVW, 2020, by TU Delft – Ports and Waterways licenced under CC BY-NC-SA 4.0).

Transition from straight reach to a bend

It is recommendable for a good view and nautical comfort to broaden the bend at the inner bank if possible. The transition from a straight section to the widened bend has to evolve gradually, preferably under a slope of 1:20 (Figure 2.29). The transition length for $R_{bend}/L_s > 6$ (preferred profile) is $2 \cdot L_s$.

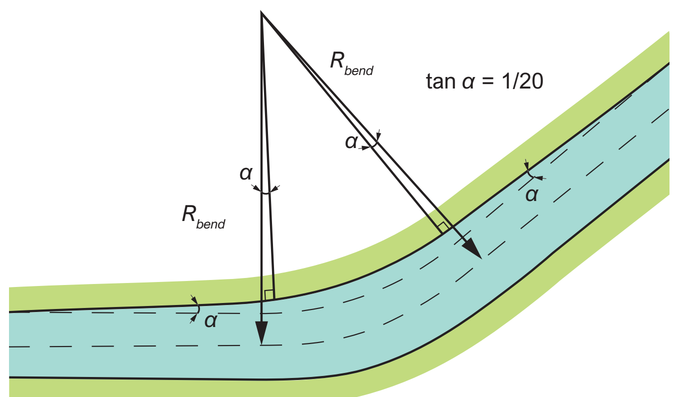


Figure 2.29: Transition from straight section to bend section (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

2.2.3 Natural waterways

Besides discharging water, ice, sediment, dissolved matter, et cetera, rivers also serve navigation purposes. This requires an integral approach of river management. Nevertheless, a fluvial waterway has to meet a number of requirements which are often not met in natural rivers. So, in general, rivers used for navigation need to be modified (Figure 2.30). This ranges from small interventions to complete control of the water level, permanent regulation of the bed geometry, or even canalisation.

Few waterways, whether natural or manmade, have been developed for navigation purposes only. Generally, there are combinations with other functions, such as irrigation, drainage, drinking water supply, fishing, energy generation, flood control, recreation et cetera. The present trend towards integral river management, aimed at balancing the interests of all functions, may mean that not all future needs of inland navigation can be met.

In this section we focus on the differences between canals and rivers as far as navigation is concerned. We will show that navigation on rivers is far more complicated. The varying water depth is only one complicating factor, as may appear from the characterisation below. Furthermore, we will indicate a number of measures to facilitate navigation on rivers.

Figure 2.30: One of the Rhine branches, the River Waal, with inland navigation (Image by Rijkswaterstaat).

Navigation on rivers

Although river types vary widely, a typical navigable river can be characterised as follows (also see Figure 2.31). Starting downstream the lower course is often the most suitable for navigation. As compared with the situation further upstream, it generally conveys more water, the bed slope is smaller and the water depth and the cross-sectional area are larger. Where a river debouches into the sea, tidal currents and swell may cause hindrance and sometimes hazardous situations.

Going further upstream the time-variation of the discharge is felt ever more, especially in times of drought. The bed slope increases, current velocities increase, water depths and cross-sectional areas decrease and the river becomes more winding and irregular with islands, shoals, multiple channels, et cetera.

These changes reduce the navigability: decreasing allowable draughts, increasing engine power requirement and more difficult manoeuvring, especially when passing through bends and sections with strong width variations.

Contrary to canals, the river bottom is not always parallel to the water level. Locally, shoals and holes may occur, and in bends the water depth in the outer bend is significantly larger than in the inner bend. In the transition between consecutive bends, a shallow bed ridge may occur and sometimes even one or more islands. Such a transition is often indicated as a crossing (see Figure 2.32).

Especially when the river bed is forked (cross-section II in Figure 2.32) these crossings can be very inconvenient. The most shallow sections determine the least available depth and are thus decisive for the permissible draught, hence the loading degree of the ships.

The 30% under keel clearance requirement does not apply to local shoals. A ship sailing downstream can pass the shoal by floating along with the current. By reducing the ship's speed, the water-level depression and therefore the squat and trim are also reduced. However, sufficient pressure has to be maintained on the rudder for manoeuvrability. Therefore, the ship needs to sail at a navigation speed a little higher than the current velocity.

Passing a shoal when sailing upstream is more problematic. In order to make progress, the ship has to overcome the current velocity, so it will generate a return current which will cause squat. At a shoal, the helmsman will therefore reduce the ship's speed to just above the current speed.

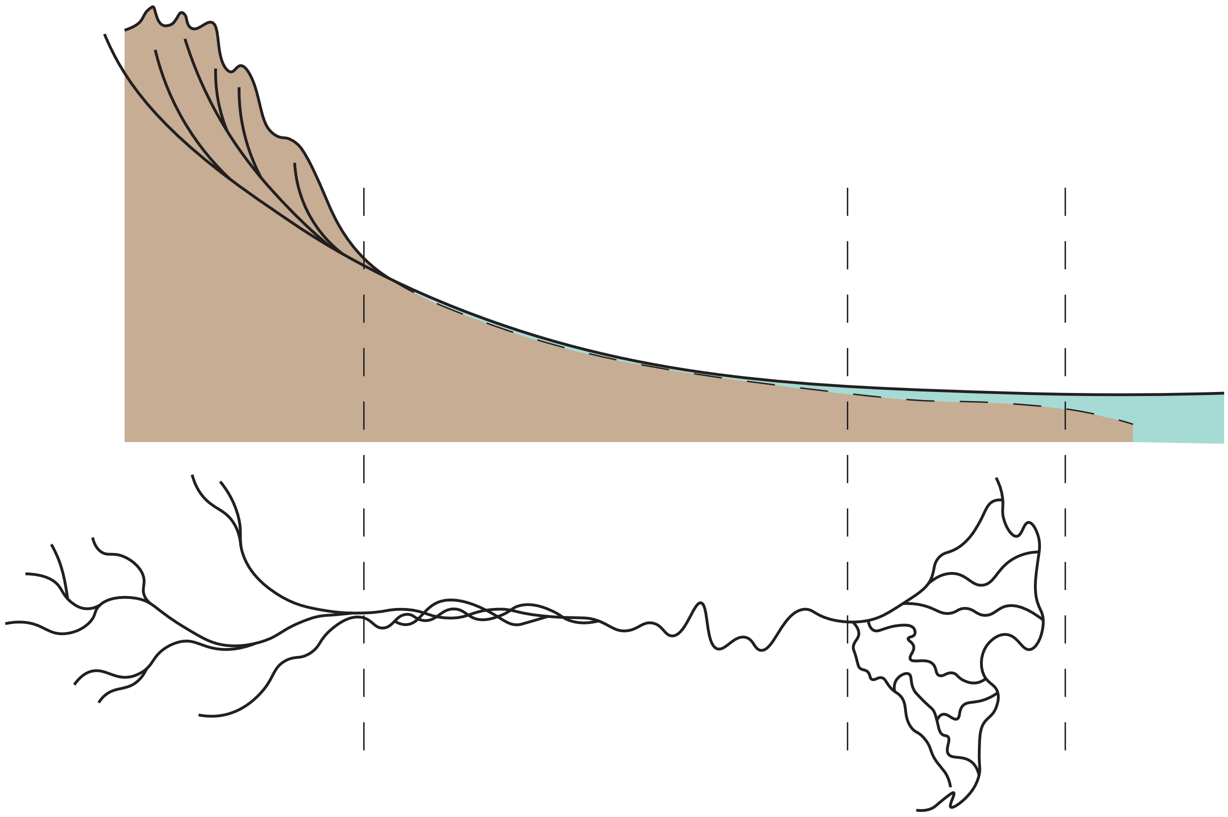


Figure 2.31: An idealised river (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

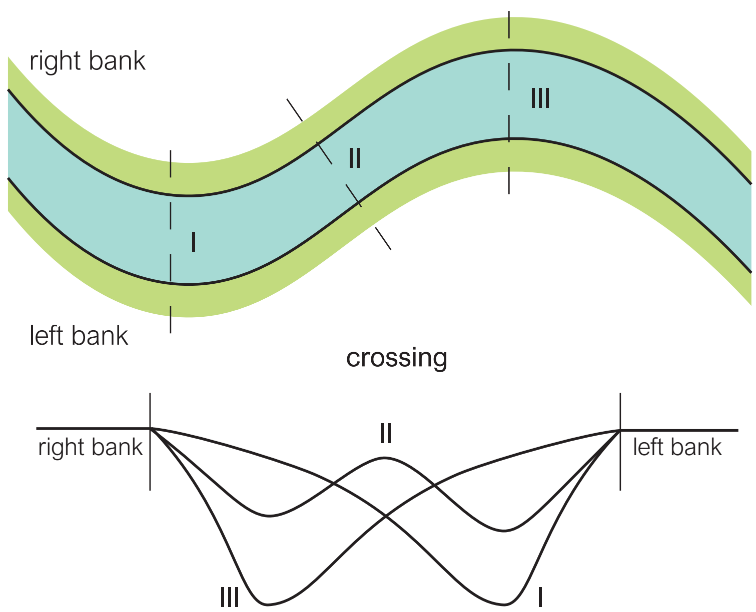


Figure 2.32: Crossing between consecutive bends in a meandering river (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

On a river the technique of navigation differs considerably from that in a canal. As shown in Figure 2.33 a vessel sailing upstream will typically navigate in that portion of the channel with the least current velocity, in order to save fuel and make progress. In contrast, a vessel heading downstream will navigate in the zone of maximum current velocity. This may involve an extra complication, viz. crossing pathways. On the major European inland waterways this has led to the practice of 'blueboarding': a ship carrying a blue sign indicates that it will pass at starboardside from the encountering vessel, instead of portside. In the design of river adaptations for navigation due attention should be paid to local practices and regulations, also regarding channel and bank stability.

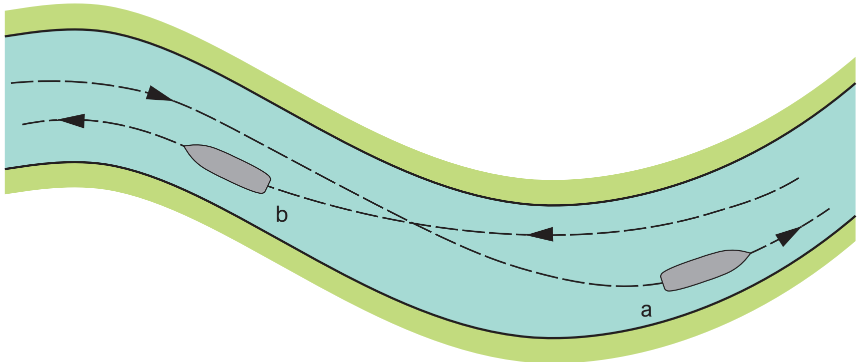


Figure 2.33: Course of vessel sailing downstream (a) and upstream (b) on a river (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Bends involve extra complications. Especially the width can be restrictive for navigation. Floods may aggravate this, because during a flood the outer bends erode further, the inner bends accrete and the crossings become more pronounced. After the flood wave has passed, the opposite phenomenon occurs. The shoals will erode and the deeper parts accrete.

A further complication concerns the visibility of the shoals, which is often poor on natural waterways. Rivers often have multiple channel systems separated by sandbanks. At high water levels a channel may be hard to find. Moreover, these channels tend to constantly change their course, which sometimes makes it necessary to shift the fairway from one channel to another. Changing channel systems are especially troublesome if a river is sailed on occasionally.

Sometimes navigation from the main stem onto a tributary is hampered by sandbanks temporarily blocking the access. Banks and mooring places may become temporarily inaccessible due to sandbanks in morphologically active rivers. If inaccessibility cannot be allowed, banks and mooring places may have to be adjusted or moved due to more suitable places.

Adaptations for navigability

River adaptations are often necessary for further traffic development. Such adaptations, however, often involve considerable costs. These costs cannot always be justified by the expected traffic development in the near future. That is why adaptation plans are sometimes realised step by step, such that each step gives enough stimulus for further traffic development to justify the costs. Supply of better information on the navigation situation is often a first step.

Information for navigation Fairway authorities should have their own patrol service (or hire a private organisation) in order to provide information on the state of the fairway. Echo soundings have to be made regularly in the channel and at shallow locations. Regular announcement of least available depths on all important fairway stretches is necessary. Buoys, beacon systems, signs and signals have to be installed and maintained, as well as traffic control systems like FIS and VTS (see Chapter 5).

Buoyage should follow the so-called lateral system, indicating the channel borders, instead of the cardinal system focusing on dangers. Buoys can best be placed on the steep side of the ,profile; buoys on both sides of the channel are only required when it is very narrow or crowded. Especially reaches with a migrating fairway must be properly marked with buoys. Shipping at night can be facilitated with navigation lights along the banks that mark the channel.

It is important to make maps of the waterway available to users. On board of vessels there is only need for a rather simple map (situation of channel, buoys, beacons, signs, headroom, depths in harbours, kilometres, et cetera). The authorities need more detailed maps, including the whole floodplain, as a basis for a good river management.

Current information, particularly on least available depths and water level forecasts, is provided via internet, regular broadcasting programs and printed reports. Such information is crucial to determine the maximum draught of a vessel heading for a certain destination. At the same time special messages can be announced (new or moved buoys, obstructions, accidents, temporary works, et cetera).

Very High Frequency (VHF) radio is necessary for ships to maintain regular contact with traffic control centres, other ships and offices in ports and terminals. Therefore, a system of radio masts along the controlled fairway has to be installed and radio-channel frequencies have to be reserved.

Radar on board of vessels can be useful to get an overview of the other traffic, when navigation at night is expected, or when visibility is poor due to mist, heavy rainfall or sandstorms. It requires special attention to buoys, beacons and bank alignments, which must give a good radar echo at all stages and under all weather conditions. A shore-based radar chain as part of the VTS system can also enhance navigational safety.

Internet-based information systems are used to communicate information on passing vessels and their cargo to traffic control centres and lock and bridge operators. This saves skippers waiting time and reporting the same information at every control point on the route, and it enables lock operators to use their locks more efficiently. In case of an accident, the information enables immediate and appropriate action.

Improvement of the waterway Adaptations to natural waterways should be carried out with considerable caution. Rivers are dynamic systems, responding at a wide range of temporal and spatial scales. This means that the effects of an intervention may only manifest after some time and at various places along the river. Such interventions therefore require a thorough understanding of the dynamics of water and sediment. Mistakes may necessitate costly correction works and continuous maintenance.

A first step in improving the navigability of (alluvial) rivers could be dredging. Dredging can be divided into maintenance dredging, recurrent dredging and capital dredging.

I. Dredging

Maintenance dredging To maintain a reasonably stable channel, some dredging is inevitable. Location and amount of this type of dredging cannot be foreseen; it is basically a response to problems where they pop up. In the case of a new fairway it is recommendable to have a dredger of suitable capacity stationed nearby. After some time, the order of magnitude of the maintenance dredging volume can be estimated on the basis of experience. It will then be possible to choose the most suitable equipment.

Recurrent dredging As opposed to maintenance dredging, the locations of recurrent dredging are known. Often the least available depth is found at a crossing, where the thalweg (i.e. the locus of the deepest points per cross-section) moves over to the opposite bank. Recurrent dredging of the critical crossings in a river may increase the least available depth for the entire fairway.

The previous section described how flood waves can affect the navigability of rivers. Therefore, recurrent dredging should preferably be done shortly after the flood season. The dredged material can then be deposited in the (too) deep outer bends nearby.

Generally speaking, systematic extraction of the dredged material from the river system has detrimental large-scale and long-term effects on the river, especially on its bed slope. The dredged material should therefore be brought back into the river. The place where this can best be done depends on the situation and requires a thorough insight into the river's dynamic behaviour.

As a first step to river adaptation, recurrent dredging has advantages over more permanent interventions, such as engineering structures. It is flexible, the costs are low, and it gives insights into the river's response.

Capital dredging A one-off dredging operation needed to create a new navigable channel in a river, or to enlarge an existing one, is called capital dredging. Capital dredging is usually a large operation constituting a significant intervention in the river system.

II. Discharge regulation

A well-aligned river will accommodate low and high discharges, including flood conditions. A natural, uncontrolled river will shape itself according to the sediment supply from upstream, the discharge regime, the bed and bank composition and the downstream water level. The result, however, is not always suitable for navigation or the other functions man has attributed to the river. This is why we tend to 'improve' it.

Discharge regulation may be an attractive measure for navigation, but there are a few prerequisites. Firstly, the total annual run-off in a rather dry year should be large enough to keep the river navigable for a significant part of the time. Secondly, sufficient reservoir storage should be available upstream of the navigation route to significantly attenuate a flood wave.

Consider a hypothetical river with a single flood period per year and a typical discharge hydrograph as in Figure 2.34. After the dry season, the river become becomes navigable at point a. Towards the end of the flood period, the channel system is disturbed and the river becomes unnavigable at point b, at a higher discharge level than point a. In practice navigation will stop earlier, say at point c, so as to avoid the risk of running aground on a river bed that has undergone unknown changes. If the entire flood volume could be stored, the channel system would hardly change because the discharge would be kept approximately constant. In that case the river remains navigable until point d. In practice this will be difficult to realise, if only because of the very large storage volume required.

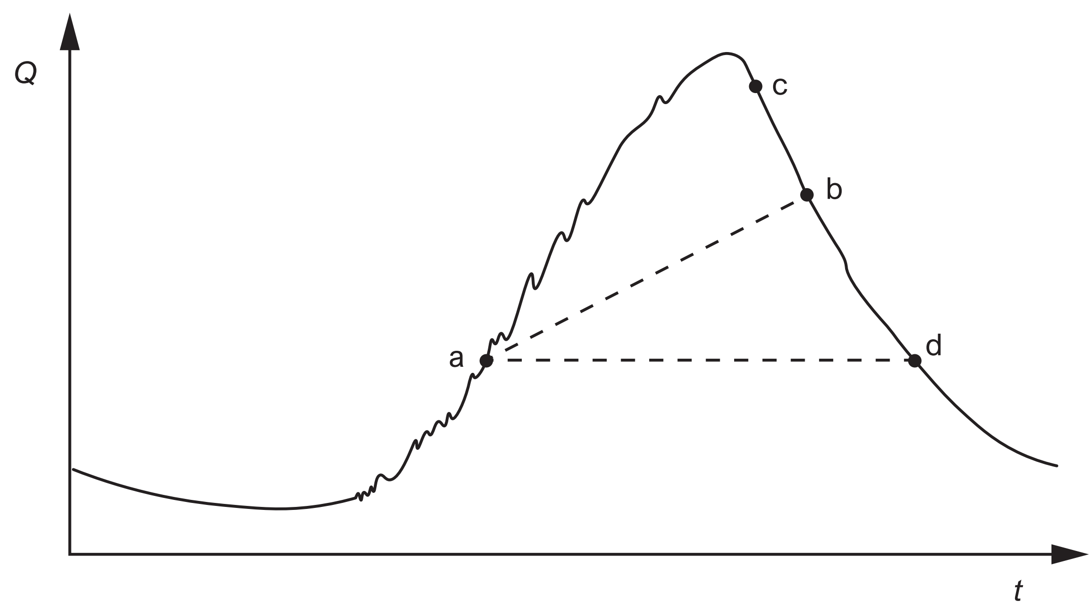


Figure 2.34: Discharge hydrograph of a hypothetical tropical river (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

An important aspect of discharge regulation is how to release the stored water after the flood season. The most common strategy (Option 1 in Figure 2.35) is to start releasing at the end of the flood season and maintain a constant discharge in the river, high enough to keep it navigable until the reservoir is empty or back at the water level to be maintained in the dry season. Once that point is reached, navigation may temporarily become difficult.

Since storage reservoirs are usually of a limited size, it may be impossible to store the total flood volume in an unusually wet season. In that case, the surplus flood water has to be passed on to the river, where it adds to the basic discharge and may cause disturbances of the river bed.

Depending on the demand for navigation, other strategies may be chosen. If the demand is highest towards the end of the dry season, for instance because the harvest needs to be transported, one may decide to retain the flood volume in the reservoir and release it only towards the end of the dry season.

Another possibility, if there is mainly downstream navigation, is to release the stored water in pulses (Option 2 in Figure 2.35). Downstream sailing vessels can 'ride' the flood waves generated by this strategy.

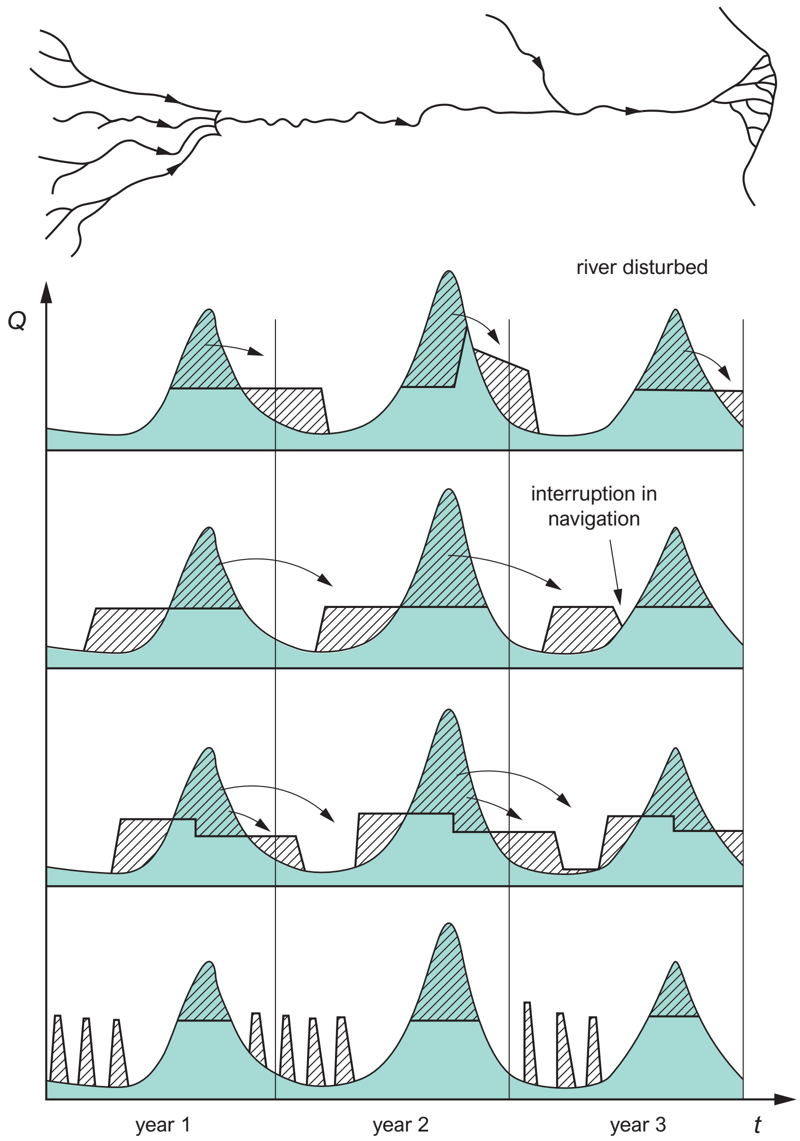


Figure 2.35: Storage release strategies (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Since man-made reservoirs in rivers are expensive facilities, they are usually not built for flood water storage alone. Often they also serve hydropower production and irrigation purposes. This means that storage and release of water is not optimised for downstream navigability alone. This may lead to conflicting interests and undesired situations. The Three Gorges reservoir in the Yangtze River, China, is such a multi-purpose reservoir. Before the flood season, the water level is lowered in order to accommodate the flood water, but if the flood does not come, like in the dry year 2006, the reservoir has to be filled back to the level required for hydropower production at the expense of the discharge downstream of the dam. This constitutes a risk for functions downstream, for navigability, but also for drinking water intake, for instance.

III. Permanent regulation works

Permanent regulation works exist in many forms. Bank protection is one example, groynes and Longitudinal Training Dams (LTDs) to fix and confine the main channel are others. Examples of in-channel regulation works, are outer bend fills and bottom groynes, both meant to enhance the water depth in the inner bend.

When a river is locked into a set planform by such regulation works, its natural migration in the horizontal plane is stopped. This leaves only the bed for adjustment to changing conditions. Such bed responses can take place at a variety of scales, from bedform development at a scale of metres to large-scale tilting at a scale of many kilometres.

It takes a good insight into the dynamics of a river, sometimes supported by numerical models, in order to predict what the effect of certain regulation measures will be and at what spatial and temporal scales they will become manifest.

Permanent regulation works are costly operations. In order to make them economically feasible it may be necessary to also serve other purposes, such as flood protection, harbour development, freshwater supply, road and railroad crossings, et cetera.

Figure 2.36 gives two examples of river regulation works, one for the river Waal, the Netherlands, and the other for the river Vistula, Poland. They also illustrate how long it may take before a river is fully regulated.

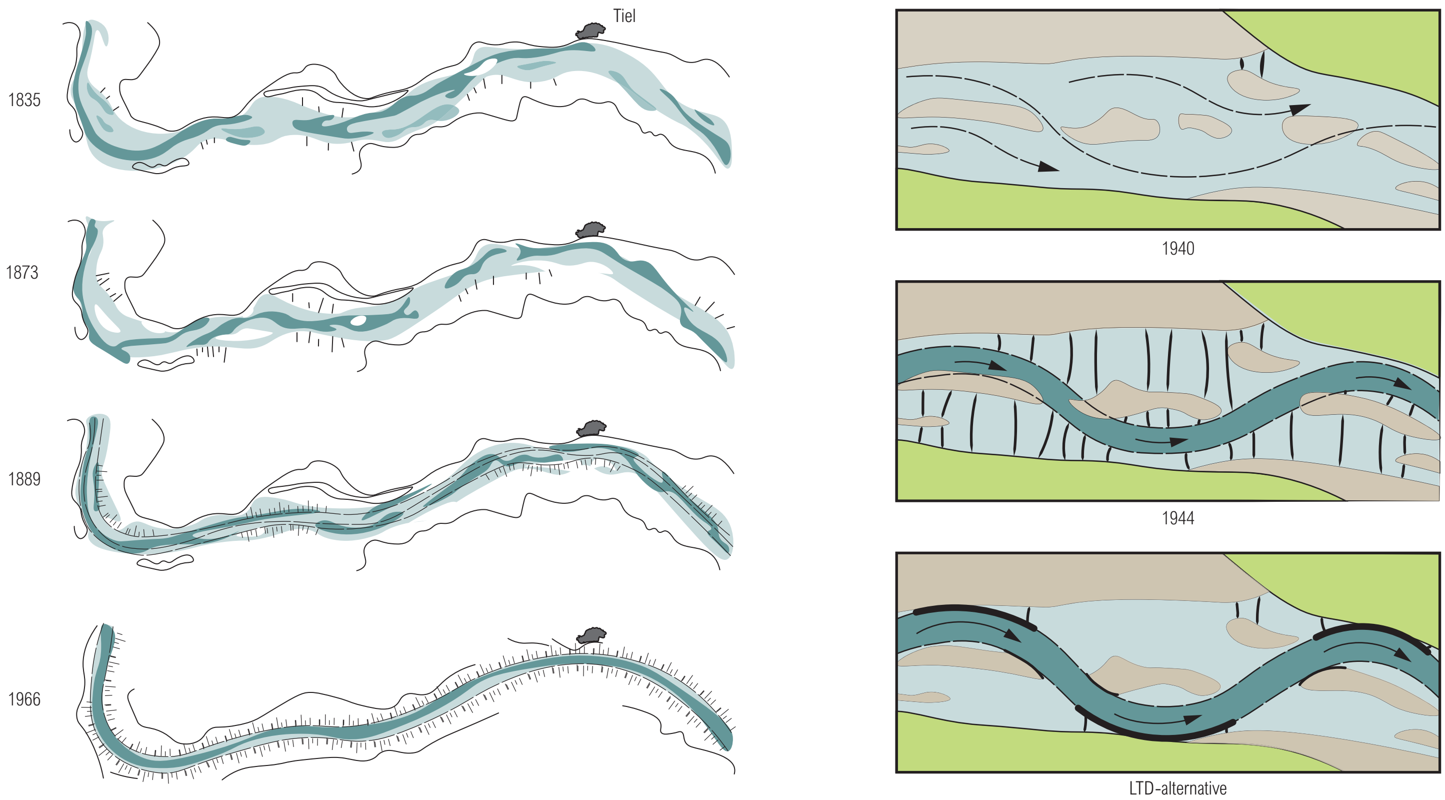


Figure 2.36: River normalisation. Left: River Waal (reworked from Jansen et al., 1979); right: River Vistula. Images by TU Delft – Ports and Waterways licenced under CC BY-NC-SA 4.0.

For a long time, groynes have been considered suitable means for river training (see Figure 2.37), but they turn out to have a number of disadvantages. Their very purpose, viz. to confine the main channel and concentrate the flow under normal conditions, positively influences water depth and navigability, but it also enhances the river's sediment transport capacity. If more supply from upstream is lacking, the river gradually reduces its slope and incises upstream. Consequently, groynes there become unnecessarily high, causing undesirable resistance under flood conditions, and in-channel structures stick out of the bottom and become obstacles to navigation. In the case of the Rhine branches in the Netherlands this has led to costly groyne lowering schemes, as well as to a pilot project with longitudinal training dams detached from the banks.

IV. Canalisation

A canalised river is equipped with weirs combined with locks to control the water level in times of low discharge. Like discharge regulation and permanent regulation works it is a costly solution. An example of a canalised river is the river Maas in the Netherlands (Figure 2.38).

An important downside of natural waterways is that they sometimes don't give access to the final destination of the transported goods. In that case, either other transport modalities are required for further transport, or a connecting canal has to be built.

Figure 2.37: The river Waal, normalised with groynes (Rijkswaterstaat).

Figure 2.38: Canalised river Maas, the Netherlands (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Sometimes two navigated rivers are connected, such as the Rhine and the Danube, which are connected by the Rhein-Main-Donau Canal. Such a canal often contains a number of locks, in order to approximately follow the relief. At the intersection of a river and a canal, a sluice is usually required to keep the fluctuating water level of the river from penetrating into the canal.

Sometimes canalisation works are multi-purpose. The weir can be combined with a bridge, like in the case of the weir near Grave in the river Maas (Figure 2.38, left: second from the top). Also, the head difference over a closed weir may be used for low-head hydropower generation, like in the case of the Maas-weirs near Linne and Lith (Figure 2.38, left: first from the top, and right: last on the right).

2.3 Dimensions of water areas in sea ports

The previous subsections discussed ship behaviour and how this affects the dimensioning of efficient and safe inland waterways. Of key additional importance to waterborne supply chains are the dimensions of water areas in the ports, the typical begin and end points of each journey. This section addresses the dimensions of water areas in sea ports. The next section addresses inland ports. Much of the material presented in this section has been derived from or inspired by the PIANC report 'Harbour approach channels design guidelines' (PIANC, 2014c) and Ligteringen (2017).

2.3.1 Port approach channel

When approaching a port from the open sea, a vessel may have to cross a shallow coastal zone (Figure 2.39). The fairway across that zone is often maintained artificially at a certain width and depth. But even in case of a deep-water port the actual entrance has to be protected against waves and currents. Breakwaters serve this purpose well, but by definition they confine the access. In view of the complex local wave and current conditions at the transition between open and sheltered water, the shape and dimensions of this access are critical to safe navigation.

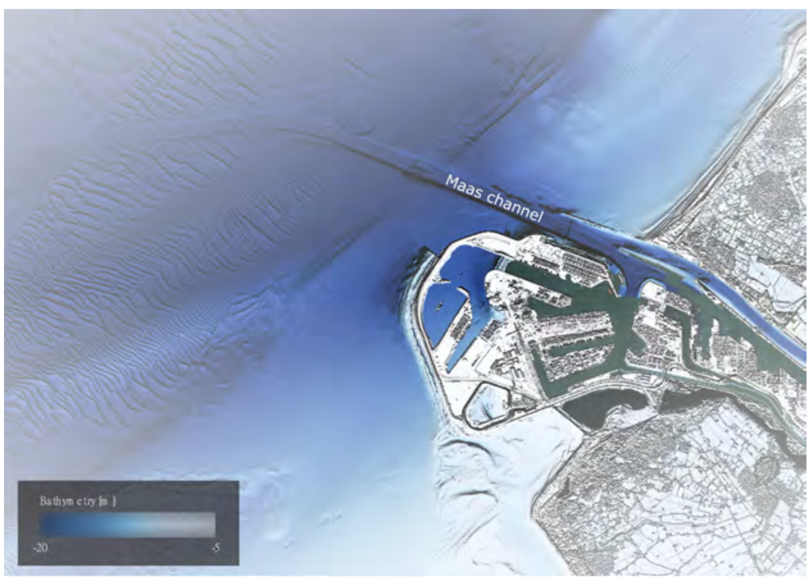


Figure 2.39: The Maas channel, giving access to the Port of Rotterdam (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0). Sources: EMODnet Bathymetry (EU Directorate General for Maritime Affairs and Fisheries), RWS Vaklodingen, RWS River bathymetry 1m, and RWS Actueel Hoogtebestand Nederland.

Figure 2.40 shows the main elements of an access channel. The outer part, in open water seawards of the breakwater(s), is usually marked by lateral buoys. Bends should be avoided as much as possible, in order not to complicate navigation and to avoid extra width requirements, as this involves extra capital and maintenance dredging.

The part sheltered by the breakwater(s), the inner access channel, is the extension of the outer part. It gives access to the various harbours of the port. In order to manoeuvre towards the berth, a turning basin provides the space to turn the vessel.

In the following sections we will discuss the dimensions of the various parts of access channels, turning basins, port basins and berth areas.

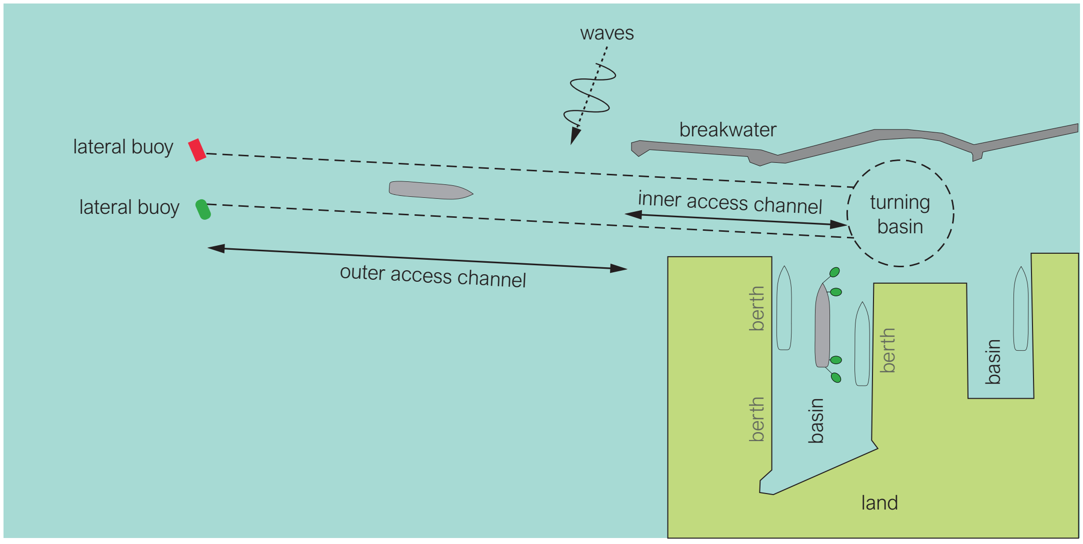


Figure 2.40: Access channel elements (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

2.3.2 Access channel width

Much like in inland waterways, the width of an access channel is determined by the following factors:

- the manoeuvring lane of the vessels,
- the swept path,
- the number of lanes,
- the passing distance (in case of multiple lanes),
- the bank clearance,
- the under keel clearance, and
- the seabed characteristics.

Tidal conditions may also play a role. Extra complicating elements in the outer part of the channel are wind, waves (sea and swell) and tidal currents. Consequently, for the outer channel the extra width components on top of the beam are generally larger than in inland waterways.

Manoeuvring lane or swept path

The basic manoeuvring lane provides space for the slightly sinusoidal path a vessel usually takes (also see Section 2.1.1). The width W_{bm} of the basic manoeuvring lane is therefore larger than the vessel's beam, typically 1.5 B_s. Manoeuvrability may differ according to vessel type, water depth, wave and current conditions, visibility and aids to navigation.

Swept path

The width W_{bm} of the swept path will generally be larger than in inland channels (also see Section 2.1.2), due to stronger winds, waves and currents. Table 2.2 gives the different width additions W_a to W_{bm} for different conditions. The numbers in Table 2.2 are from PIANC (2014c) and related to moderate manoeuvrability and low speed conditions, which are characteristic of port access channels.

Like in inland channels, the under keel clearance influences manoeuvrability. This leads to an additional width requirement W_{kc} depending on the h_0/D_s ratio: $W_{kc} = 0.1\ B_s$ for ratios between 1.25 and 1.5 and $W_{kc} = 0.2\ B_s$ for ratios smaller than 1.25. This is added to the swepth path.

The consequences of hitting the seabed differ according to its composition. Hitting soft mud will not do much damage, but hitting hard rock much more. This also translates into an additional width requirement to be added to the swept path.

Contributing factor	Condition	Width additions W_a
cross-wind	15 – 33 kn 33 – 48 kn	0.6 B_s 1.1 B_s
cross-current	0.2 – 0.5 kn 0.5 – 1.5 kn 1.2 – 2.0 kn	0.3 B_s 1.0 B_s 1.6 B_s
long-current	1.5 – 3.0 kn $>$ 3.0 kn	0.2 B_s 0.4 B_s
wave height	1 – 3 m $>$ 3 m	0.5 B_s 1.0 B_s
seabed composition	soft sediment hard material	0.1 B_s 0.2 B_s
under keel clearance	$1.25 < h_0/D_s < 1.5$ $h_0/D_s < 1.25$	0.1 B_s 0.2 B_s

Table 2.2: Additional width requirements (modified from Ligteringen, 2017).

Passing distance

In case of multiple lanes, the distance between passing vessels has to be large enough for safe navigation. The passing width W_p depends on the vessel speed: $W_p = 1.2\ B_s$ for vessel speeds between 5 and 8 knots, and $W_p = 1.6\ B_s$ for vessel speeds between 8 and 12 knots.

Bank clearance

To stay safe from the bank, a bank clearance distance is added to the channel width, depending on the bank's slope and type. For sloping banks the clearance W_b is 0.3 B_s, for steep banks and banks of hard material (e.g. breakwaters) it is 0.5 B_s.

Summary

In summary, the total width W of a single-lane access channel is given by (see Figure 2.41):

$$W = W_{bm} + \sum W_a + 2W_b \tag{2.8}$$

in which $\sum W_a$ is the sum of the different contributions W_a mentioned in Table 2.2.

Similarly, for a two-lane channel we have:

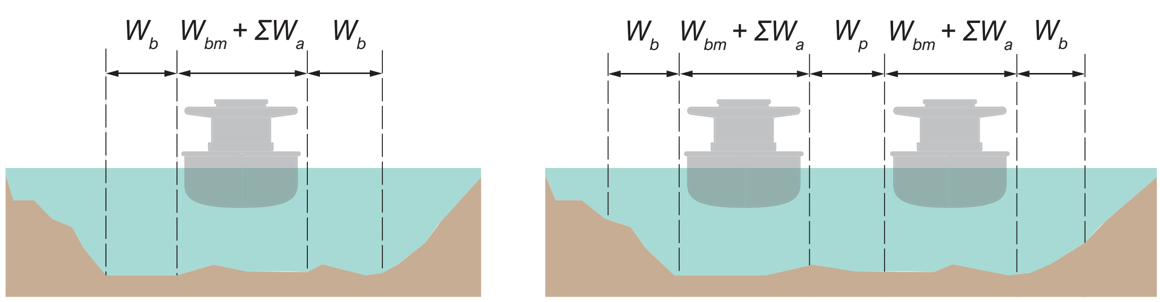


Figure 2.41: Total width of a one-way and a two-way access-channel (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

$$W = 2(W_{bm} + \sum W_a + W_b) + W_p \tag{2.9}$$

This yields outer channel widths of typically 5 times the beam of the reference vessel for a single-lane channel and 10 or more times the beam in for a two-lane channel.

In a macro-tidal environment, however, another condition may be critical. If a vessel runs aground on one of the banks, the tidal current may sweep its stern tot the other bank. If the channel is narrower than the length of the vessel, the vessel gets hung up on the banks and if this happens at hight tide, the ship may break as the tide falls. Access channels in a macro-tidal environment must therefore have a width larger than the length of the reference vessel.

Within the shelter of the breakwaters, the environmental conditions are less severe. The inner access channel can therefore have a smaller width. At the transition between the exposed and the sheltered area, however, navigation is particularly demanding. This explains why between the outer and the inner access channel a transition zone of two to three times the vessel length is required, that gives the helmsman room to adjust the vessel's course to the new situation (Figure 2.42). This applies to a situation where a strong cross current gives rise to a drift angle for incoming ships.

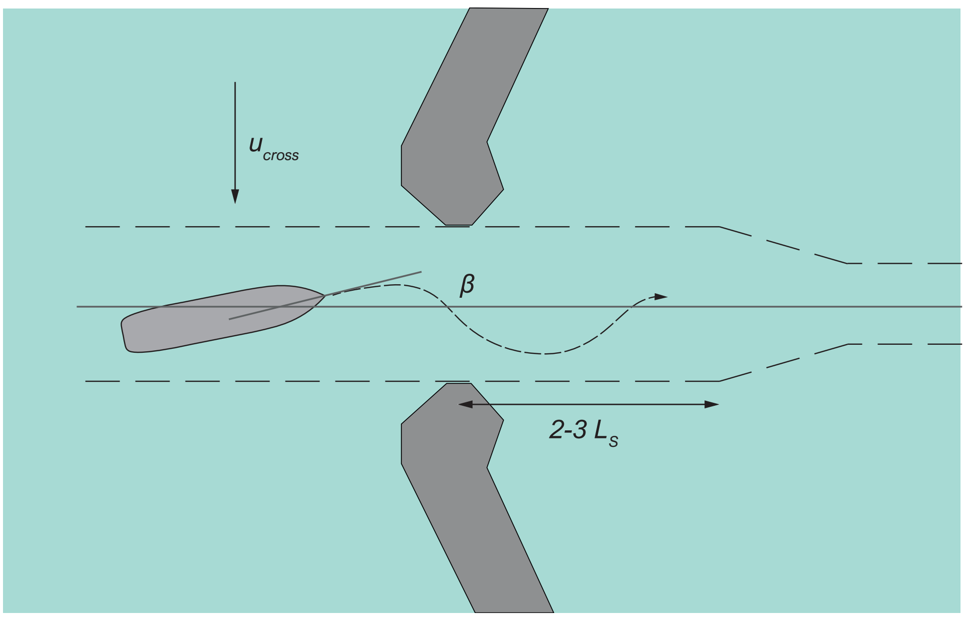


Figure 2.42: Transition zone between outer and inner channel (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Example box 2.1: Access channel design: width

Suppose we have a one-way access channel suitable for a Panamax vessel ($B_s = 32.3$ m) with the following conditions:

- cross-current at peak tide: 2 knots,
- following current: none
- cross-wind: 12 m/s,
- wave conditions: $H_s = 1.5$ m,
- traffic support: VTS,
- channel depth: 14 m dredged ($h_0/D_s < 1.25$),
- bed composition: mud.

Example box 2.1 – continued on next page

Example box 2.1 – continued from previous page

Then, applying the considerations discussed above, the total required channel width can be calculated as follows:

Component	**Width factor** ($\times B_s$)
basic manoeuvring lane	1.5
cross current	1.6
following current	0.0
cross-wind	0.6
waves	0.5
traffic support	0.0
bed composition	0.1
channel depth	0.2
implication: soft sloping banks → 2 × bank clearance	0.6
Total width factor	5.1

For the Panamax vessel in this example the required channel width would therefore be 165 m.

2.3.3 Access channel depth

Apart from the width of the access channel, it is also important to estimate its required depth. The factors determining the depth of an access channel are similar to those in case of an inland channel:

- the draft of the reference vessel at rest when fully loaded,
- the vessel's squat (sinkage, trim, heel),
- the vessel's wave response,
- the water level, and
- the unevenness of the bed.

PIANC (2014c) suggests three different methods to establish the channel depth, depending on the stage of design. In a preliminary assessment all determining factors may be lumped into a depth/draft ratio: $h_0/D_s = 1.1 - 1.4$. PIANC (2014c) gives advice on when and how to apply these ratios, as shown in Table 2.3 for swell waves.

Wave conditions	Depth/draught ratio
sheltered water	1.1 - 1.15
Hs ≤ 1.0 m	1.15 - 1.2
1.0 m ≤ Hs ≤ 2.0 m	1.2 - 1.4
Hs > 2.0 m	1.4

Table 2.3: Left: Wave effects on the depth/draught ratio (derived from PIANC, 2014c). Right: image from www.shipspotting.com, by Sushkov Oleg.

In the port planning phase, each factor should be considered in more detail and added using a deterministic formula:

$$h_0 = D_s - T + s_{max} + r + m \tag{2.10}$$

in which:

h_0 = guaranteed depth [m], usually with respect to Chart Datum,

D_s	=	draught of the design vessel at rest [m],
T	=	tidal restriction [m],
s_{max}	=	squat; rule of thumb: 0.5 m,
r	=	response to waves; rule of thumb: 0.5 H_s,
m	=	safety margin / minimum under keel clearance [m]: 0.3 m for a soft bottom, 0.5 m for a sandy bottom and 1.0 m for a rocky bottom.

Chart Datum is the level of the lowest astronomical tide, so water levels can only be lower due to meteorological effects. The tidal restriction comes into play if vessels are only allowed into the port during a certain period around high water, the tidal window (Figure 2.43).

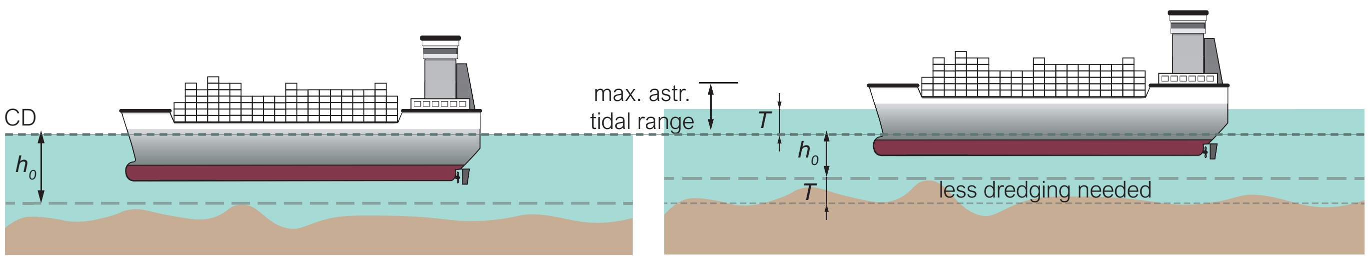


Figure 2.43: Access channel depth without (left) and with (right) tidal window (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Using a tidal window reduces dredging costs, but it increases waiting times, so port operators and shipping companies are generally not in favour of it. In the final design phase, a risk-based approach with a probabilistic model is recommendable (see also De Jong, 2020).

Example box 2.2: Access channel design: depth

According to the rule of thumb, the required depth of an access channel for vessels with 12 m draught and a representative swell wave height $H_s = 2\ m$ amounts to $1.3 \times 12 = 15.6\ m$.

If, furthermore:

- squat: $s_{max} = 0.5\ m$,
- wave response: $r = 0.5\ H_s = 1\ m$,
- tidal restriction: $T = 0$, and
- sandy bottom $\rightarrow m = 0.5\ m$,

the planning phase formula yields a required depth of $12 + 0.5 + 1.0 + 0.0 + 0.5 = 14\ m$.

So the rule of thumb is on the safe (but also expensive) side.

2.3.4 Stopping

When approaching a port, a vessel has to come to a full stop, in order to be manoeuvred to the berth by tugboats. Stopping a large vessel is not a trivial matter, because of its large inertia. Even though it will have slowed down while still at sea, it has to maintain a certain speed for manoeuvrability, especially at the transition between the exposed and the sheltered zone. So when arriving at the port entrance, it will still need some distance, L_1 in Figure 2.44, to reduce its speed to a level that enables tugboats to make fast.

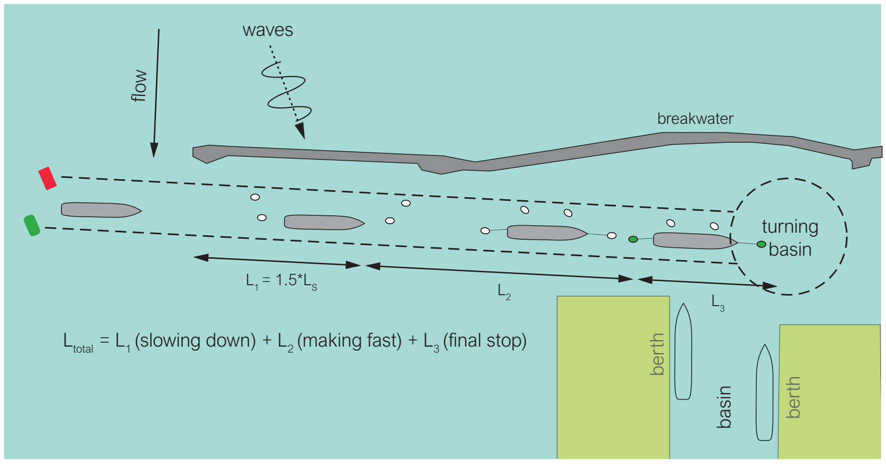


Figure 2.44: Stopping phases of a vessel approaching a port (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The speed at which the vessel arrives at the sheltered zone depends on the cross-current in the exposed area:

$$L_1 = 0.75\,(V_{\text{s, cross current}} - V_{\text{s, min}})\,L_s \tag{2.11}$$

where $V_{\text{s, cross current}}$ is the vessel's speed when entering the sheltered zone (Figure 2.45). It equals 4 times the cross-current velocity in m/s, with a minimum of 4 knots ≈ 2 m/s. $V_{\text{s, min}}$ is the speed after slowing down over L_1. It is equal to 4 knots ≈ 2 m/s. The second part of the stopping zone is meant for the tugs to make fast. In that zone the vessel's speed is still 4 knots and the fastening time is typically 10 minutes. This means that during this time the vessel moves 1200 m, which constitutes a significant part of the total stopping distance. The zone usually lies within the sheltered area, because tugs cannot make fast under wave conditions with $H_s = 1.5$ to 2.0 m (rather common in exposed water), nor can they exert any force on vessels moving at a speed larger than 4 knots. Once fastened, the tugs help the vessel to come to a complete stop. This takes a distance $L_3 = 1.5\ L_s$.

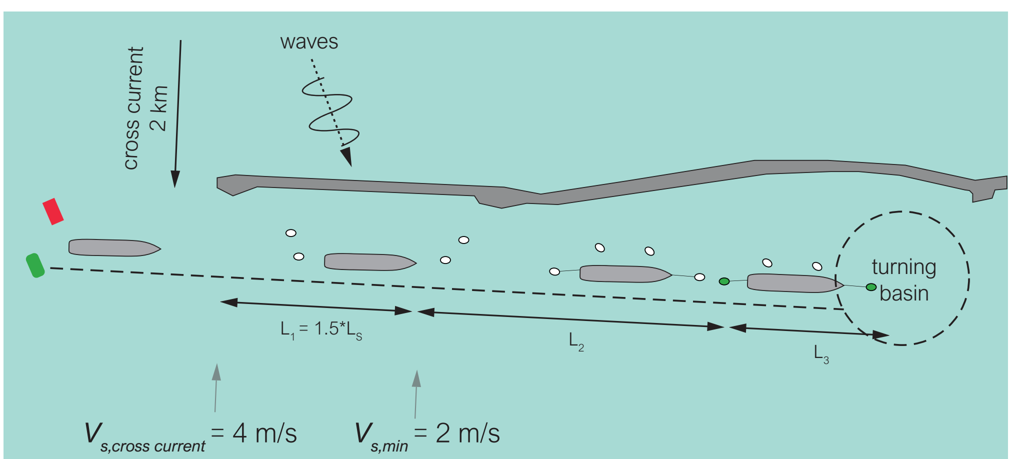


Figure 2.45: Example of the slow-down (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Example box 2.3 illustrates that the total stopping distance determines to a large extent the layout of the outer port. Therefore, more detailed navigation studies are recommended to investigate possible optimisation. Fast-time and real-time navigation simulations can be of use here.

Example box 2.3: Access channel design: stopping distance

The stopping distance for a 250 m long vessel entering the sheltered zone from an exposed area with a cross-current of 2 knots (1 m/s) can be calculated as follows:

[noitemsep] **Component**	**Contribution (m)**
initial speed when entering the sheltered zone: $4 \cdot 2 = 8$ knts (4 m/s)	
slow-down to 4 knts (2 m/s): 0.75 (4 - 2) $L_s = 1.5\ L_s$	375
making fast: 10 mins · 2 m/s	1200
to full stop with tug aid: 1.5 L_s	375
Total stopping distance	1950

2.3.5 Turning basin

In order to bring vessels into the right position for mooring, there has to be enough space in the sheltered zone to turn them (Figure 2.46).

If the vessel is turned with tug assistance, the diameter of the turning basin can be taken equal to twice the vessel length, but wind and currents may necessitate additional room, especially for vessels with a high freeboard. Further see Part II – Section 2.4.

Figure 2.46: Turning a vessel in a turning basin (left: image by william william is free to use under Unsplash Licence; right: image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

2.3.6 Port basins

Port basins should be sufficiently wide to allow for safe manoeuvring of vessels and tugboats, also when berths are occupied. The width requirements depend on the type of vessel and terminal. For container and general cargo terminals, a rule of thumb for the basin width is 4 to 5 times B_s + 100 m (Figure 2.47). In case of high cross-winds an additional width is required. With a typical vessel beam of 50 to 60 m for the largest container vessels, the basin width will be in the order of 300 to 400 m.

For dry and liquid bulk terminals the recommended basin with is 4 to 6 times B_s + 100 m and for long basins (longer than 1 km) it is $L_s + B_s + 50$ m.

Figure 2.47: Basin width for container terminals (left: Panorama Elbe Hamburg Container In The Air City by www.maxpixel.net is licenced under CC0 1.0; right: image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

2.3.7 Berth areas

When moored for cargo handling, a vessel should be as stable as possible. Depending on the type of cargo, ship motions reduce the loading/unloading efficiency, which translates into higher costs and longer harbour residence time. Too large motions also involve the risk of line snapping, a quite dangerous event.

Ship motions in a harbour are primarily caused by waves. This can be locally generated waves, sea and swell penetrating from outside, or resonant long waves. A vessel's response to wave motion depends to a large extent on its length, as illustrated in Figure 2.48. An additional factor is the wave direction (ahead/astern or abeam). Apart from waves, strong winds may cause vessels to move when moored. This is especially the case for vessels with a high freeboard, such as container carriers.

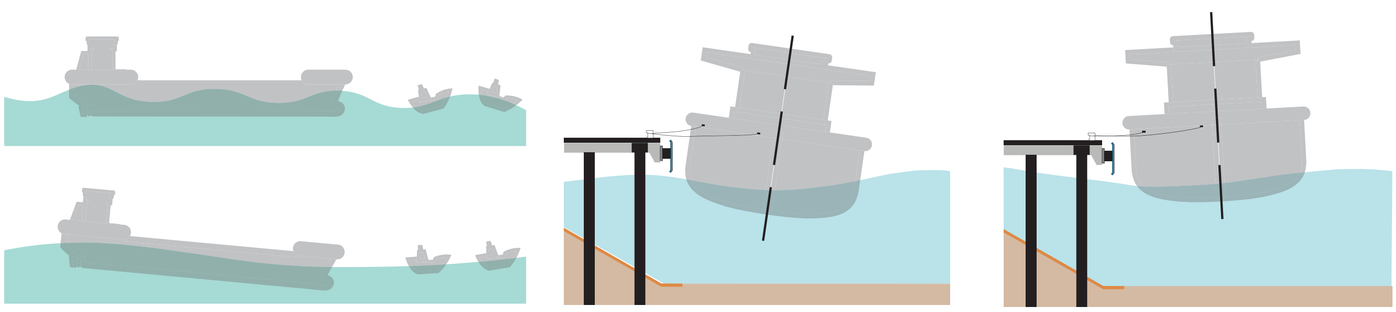


Figure 2.48: Ships in waves, left: length effect; right: moored ship in cross-waves (image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Locally generated waves need a long fetch (stretch of water in the wind direction) in order to grow high enough for hindrance. In certain elongated ports, like the one of Rotterdam, this may be the case, especially for smaller vessels such as tugboats.

Wave penetration from outside mainly happens in the channel between the breakwaters, or – in case of permeable breakwaters – through the breakwaters. Especially the longer swell waves penetrate deeper into the port area. Depending on the shape of the water bodies and the presence of wave-reflecting structures, they may resonate and even increase in amplitude. This effect is even stronger for still longer waves, such as seiches, meteorologically generated long waves with a period of 10 minutes or more. One may attempt to remediate harbour resonance problems once they occur by creating wave-absorbing elements such as run-up slopes, but it is better to design the layout such that the phenomenon does not occur. This requires detailed wave penetration studies, using a physical scale model or a numerical model (Figure 2.49).

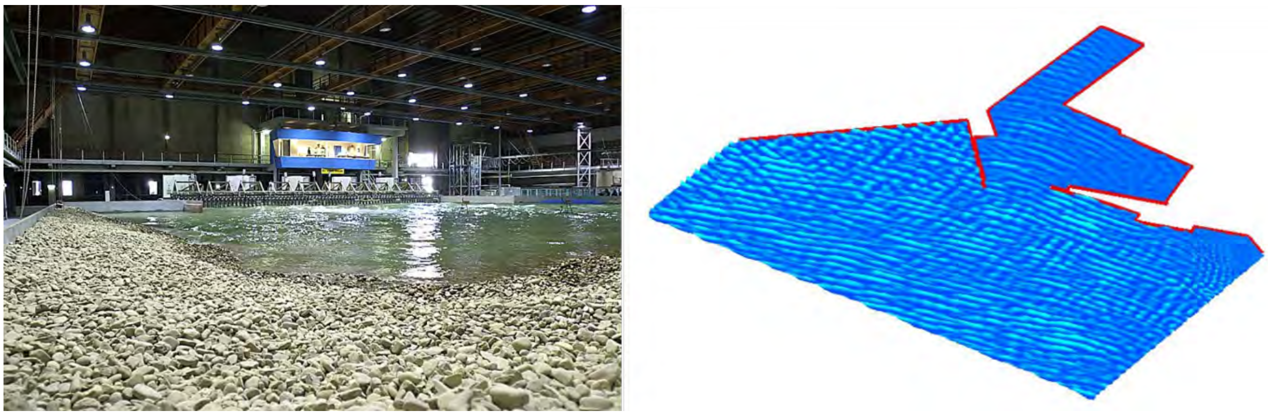


Figure 2.49: Wave penetration study tools. Left: wave basin for physical scale models. Right: numerical simulation model (left: image by Deltares; right: image by Van Vledder and Zijlema (2014) is licensed under CC BY 4.0).

The response of a vessel does not only depend on the wave height, but also on the wave period. Long vessels respond more to long waves, small vessels respond more to short waves (Figure 2.50). To calculate the dynamic response of a vessel, a Dynamic Mooring Analysis (DMA) is carried out in almost every port project. The result of the DMA shows under what wind and wave conditions downtime is expected and also what mooring forces can be expected. In Part IV – Section 4.3 we describe how simulation tools can be used in this type of analysis.

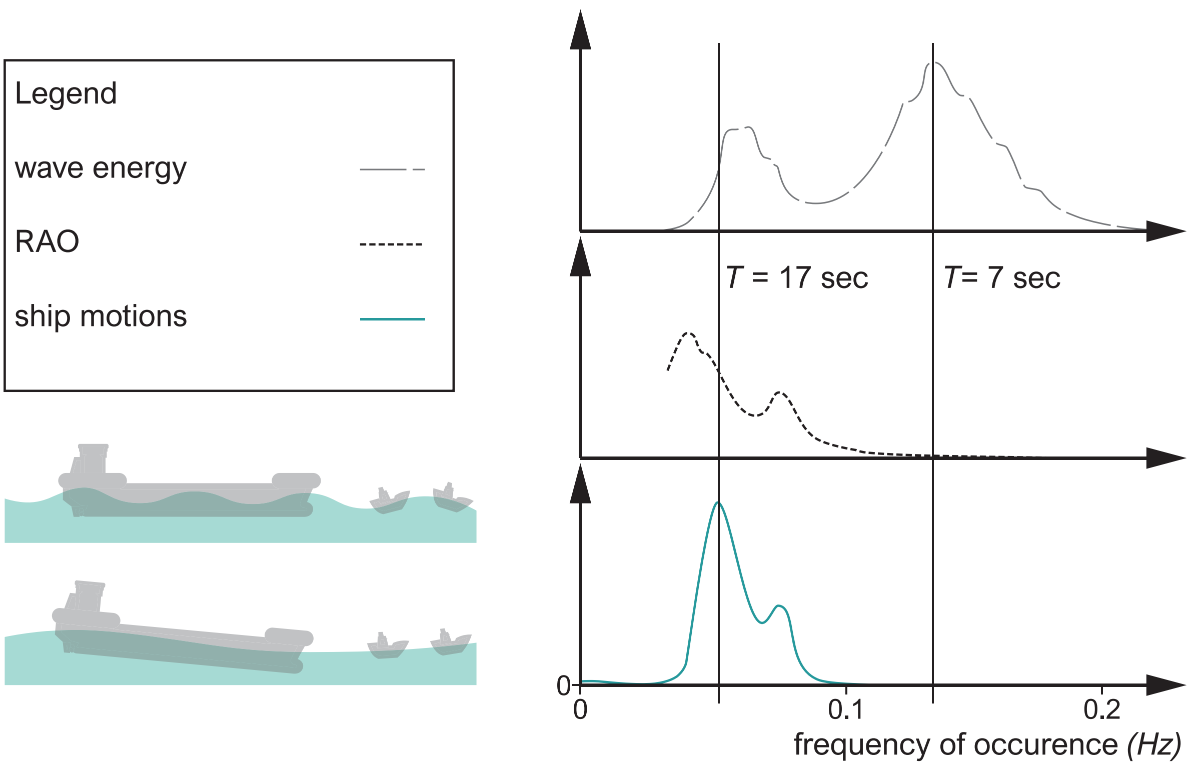


Figure 2.50: Example of a ship response spectrum for a ship sailing in deep water (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Moored vessel motions may become too large for cargo handling. Under what conditions this is the case depends on the commodity: lifting a container from deep inside the hull requires a higher precision than offloading liquid bulk using flexible hoses. If a moored vessel moves too strongly, it will be asked to leave the berth, because of the risks involved.

Table 2.4 gives the operational limits of motion of various types of vessels at berth. For each type and size of vessel this can be translated into allowable wave conditions (height, period, direction).

Vessel type	Allowable vessel motions			
	Surge (m)	Sway (m)	Yaw (°)	Heave (m)
Liquid Bulk (Tankers)	2 – 3	2 – 3	1	1.5
Dry Bulk	0.5 – 1.5	0.5 – 1.0	–	0.3 – 0.5
Container	0.5	0.3	1	0.3
Ro-Ro (at a ramp)	0.3	0.2	0	0.1

Table 2.4: Allwable motions of vessels at berth (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

If a berth is insufficiently sheltered, one may consider reducing vessel motions by using an automated or dynamic mooring system.

2.4 Dimensions of water areas in inland ports

After discussing the basic dimensions of sea ports, we will focus on inland port water areas. After a brief typology of inland ports, we address the connection to the main fairway and some key aspects of inland port water areas.

2.4.1 Typology

Inland ports vary widely in function, size and layout (also see Part II – Section 5.5). Clearly, this has implications for the water areas in and around these ports. When distinguished by function, there are:

- cargo ports, with the usual terminal types (general cargo, dry bulk, liquid bulk, containers, cars, etc.),
- industrial ports belonging to a particular factory with specific type of cargo,
- passenger ports with one or more cruise terminals,
- service ports,
- overnight stop ports, and ports of refuge.

Another categorisation is by location with respect to the fairway and the primary flood defence:

1. *berths along the fairway (Figure 2.51; also see Figure 2.55, port of Stein)* – This is only an option if the fairway is not too busy (less than 30,000 passages per year, according to RVW, 2020) and the vessels are not too large (smaller than Class V).

Figure 2.51: Berths along the fairway (Waalkade, Nijmegen by Michielverbeek is licenced under CC BY-SA 4.0).

2. *ports outside the dike, so in a river floodplain (Figure 2.52) or along a canal* – The terminal area has to be reclaimed (heightened), which makes it rather expensive. Furthermore, the dimensions of the floodplain determine the space available for expansion. When located on a canal, these harbours are always accessible, but when located on a river there may be downtime due to extreme floods (strong currents over the floodplain) or extreme droughts (too low water level). On a river, sedimentation in and near the mouth of the access channel may be a problem. Finally, the reclaimed area may be an obstacle to floods, thus reducing the river's flood conveyance capacity.

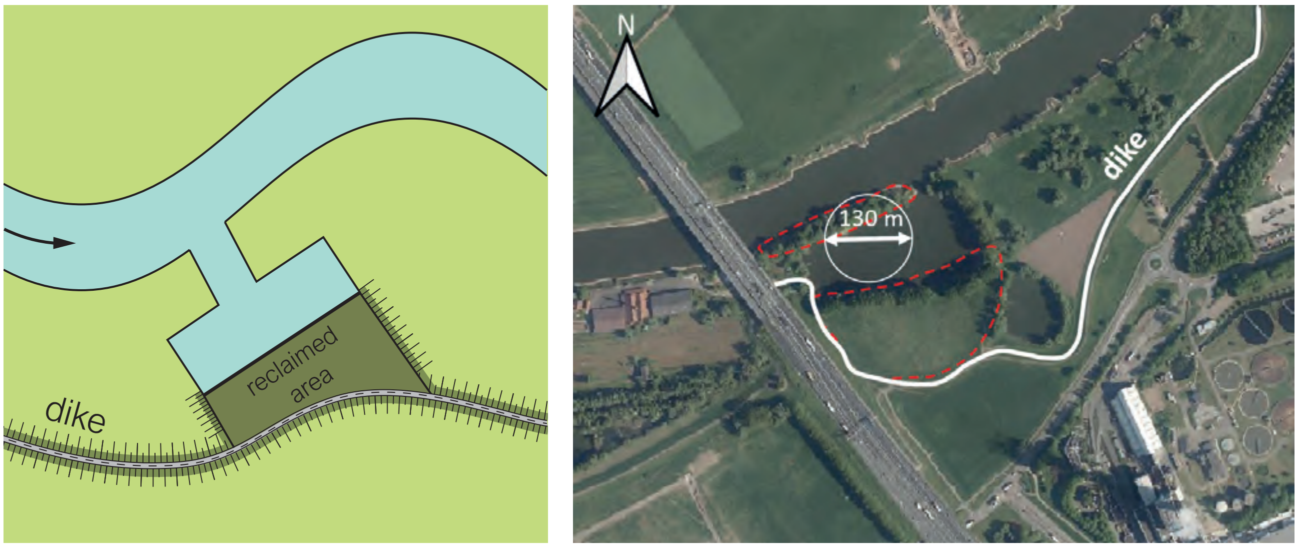


Figure 2.52: Floodplain port; left: principle; right: projected port near Westervoort on the river IJssel (left: reworked from Ligteringen, 2017, by TU Delft – Ports and Waterways licenced under CC BY-NC-SA 4.0; right: Aerial imagery background by the National Georegister (NGR) is licenced under CC BY 4.0).

3. *open ports surrounded by an intersection dike (Figure 2.53)* – These ports are better protected against flood currents and they don't reduce the river's flood conveyance. The other pros and cons are largely the same as for ports outside the dike.

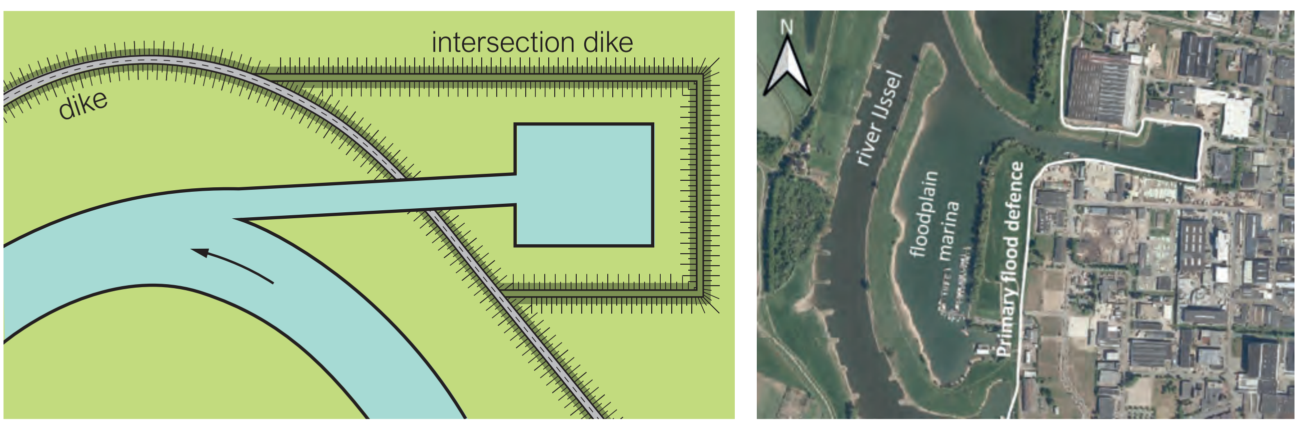


Figure 2.53: Open port behind the original dike and surrounded by an intersection dike; left: principle; right: industrial port of Zutphen on the river IJssel (left: reworked from Ligteringen, 2017, by TU Delft – Ports and Waterways licenced under CC BY-NC-SA 4.0; right: Aerial imagery background by the National Georegister (NGR) is licenced under CC BY 4.0).

4. *ports inside the dike, closed off with a lock (Figure 2.54)* – Since in this case, the water level in the port is kept constant, it is accessible as long as the lock functions. Clearly, the lock causes delays, limits the vessel size and brings costs for construction, operation and maintenance. On the other hand, berth and terminal areas are relatively cheap and expandable. In order to compensate for locking losses during low water in the river, pumping water back into the port area may be necessary.

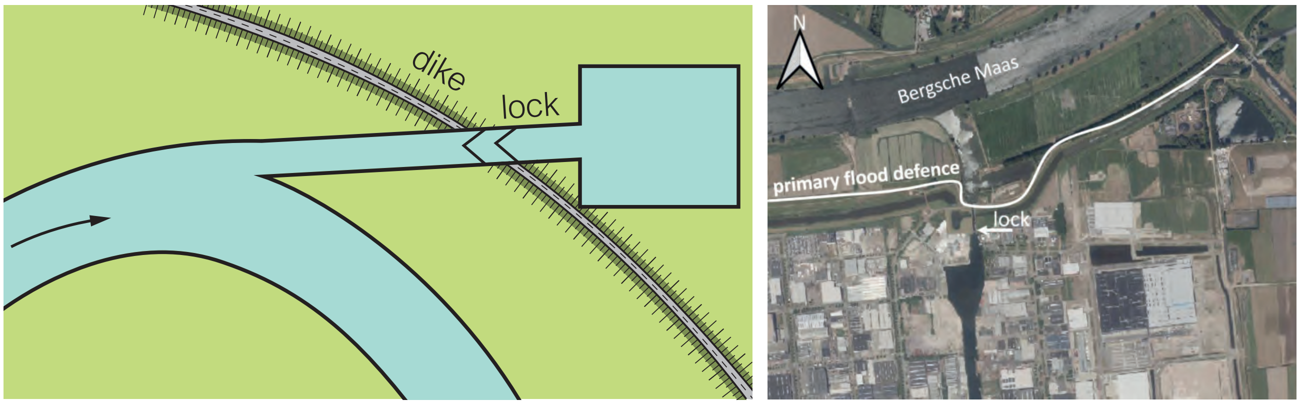


Figure 2.54: Closed port inside the dike; left: principle; right: industrial port of Waalwijk on the river Maas (left: reworked from Ligteringen, 2017, by TU Delft – Ports and Waterways licenced under CC BY-NC-SA 4.0; right: Aerial imagery background by the National Georegister (NGR) is licenced under CC BY 4.0).

2.4.2 Connection to the main fairway

It makes quite a difference whether an inland port is located on a canal, a canalised river, a regulated river with a fixed main channel or a 'wild' river with a migrating main channel (Figure 2.55). This goes for entrance and exit manoeuvres of the access channel, which are complicated by the presence of velocity gradients. It also goes for water level variability in the access channel and the port basins, and for sedimentation and navigability.

Figure 2.55: Left: Deutz harbour (GE), on the River Rhine (Deutzer Hafen, Poller Wiesen, Rheinbrcken by ToLo46 is licenced under CC BY-SA 4.0); right: port of Mlheim (GE), in open connection with the River Rhine (Mlheimer Hafen (Flight over Cologne) by Neuwieser is licenced under CC BY-SA 2.0).

In developing countries, situations can be more extreme. One example of a 'wild' river is the Ayeyarwady in Myanmar. Channels in this braided river are quite variable and often change from primary to secondary in terms of discharge and water depth (Figure 2.56).

On a river with active sediment transport, sedimentation in and near the mouth of the access-channel can be a problem. By locating the channel in an outer bend, this will be less of a problem, because the secondary flow tends to direct the transport away from the mouth. If such a location is not possible, a so-called Thijsse-egg (named after the Delft professor J. Th. Thijsse) may be a solution (Figure 2.57).

The functioning of the Thijsse-egg is based on the flow circulation inside the egg, which is separated from the main flow by a shear layer. Thus flow and sediment transport in the river are hardly disturbed and the morphological effects are negligible. The sediment that still enters the cell is transported by the secondary flow to the centre of the egg, where it piles up, ready to be removed.

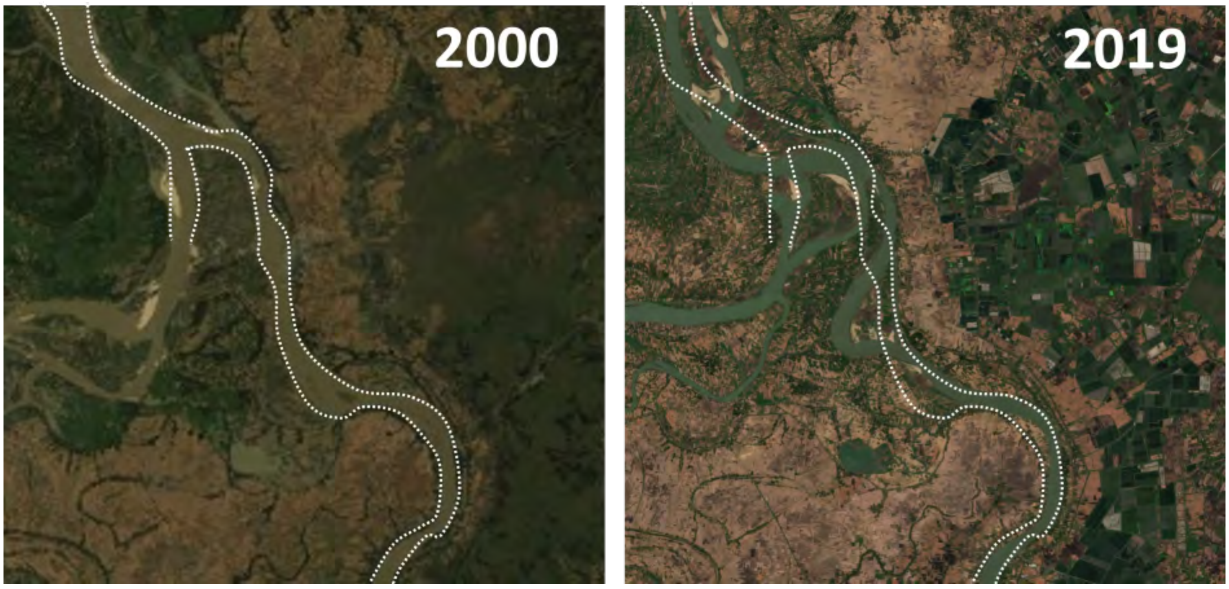


Figure 2.56: Morphology of the Myitmaka River at different points in time: where to locate a port? (left: Landsat 4-5 TM L2 image courtesy of the U.S. Geological Survey processed by Sentinel Hub is licenced under CC BY; right: 'Copernicus Sentinel data 2019' for Sentinel data is licenced under CC BY).

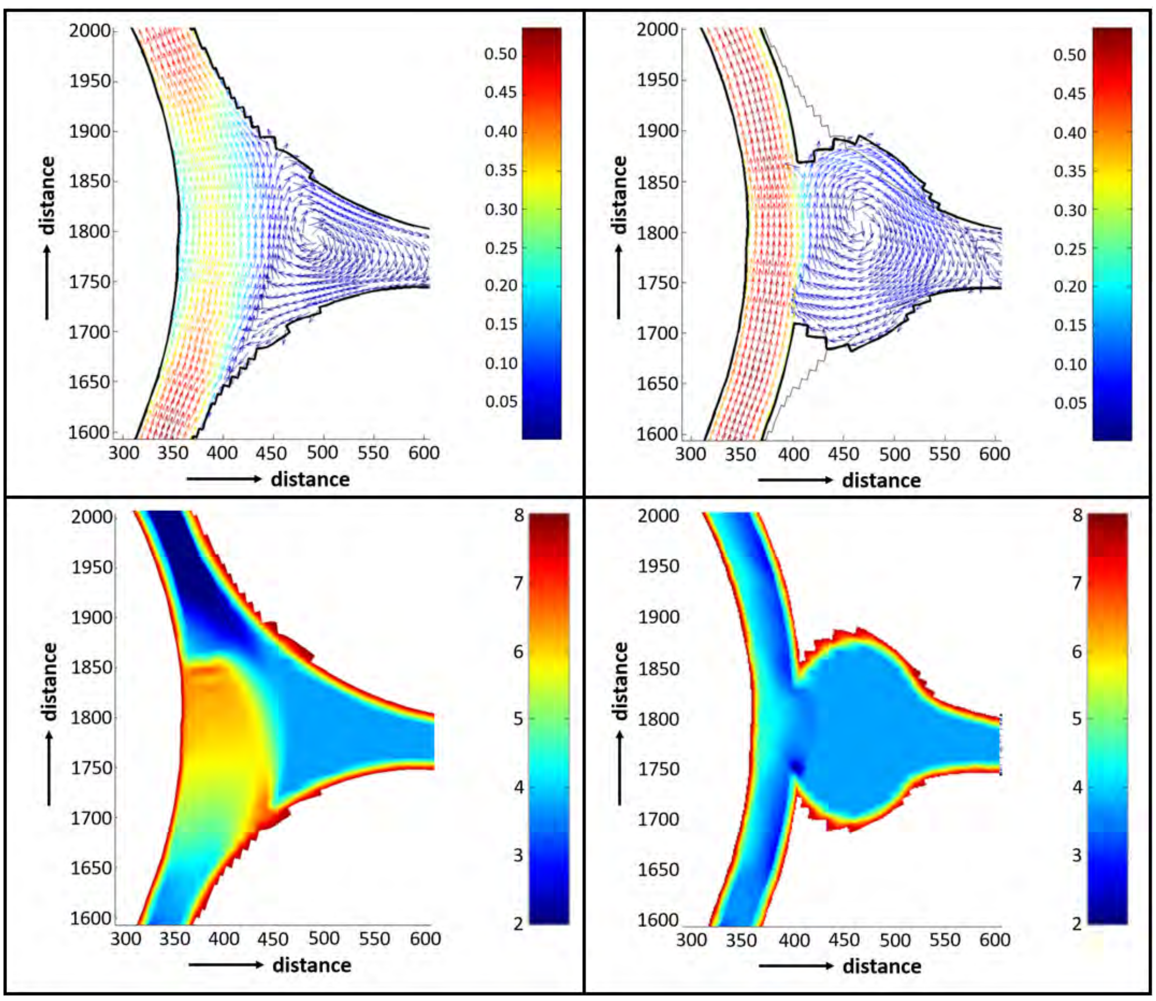


Figure 2.57: Entrance to the Emsland-Mitte Hafen near Haaren, Germany. Left: original design; right: improved design with Thijsse-egg; top: velocity field; bottom: morphology (source: Euro-Hafen Emsland-Mitte, Delft Hydraulics, report Q4072, 2006).

Apart from preventing sedimentation, the Thijsse-egg also offers extra manoeuvring space for vessels entering of leaving the access channel (Figure 2.58). Such space is needed because the vessels experience strong velocity gradients here.

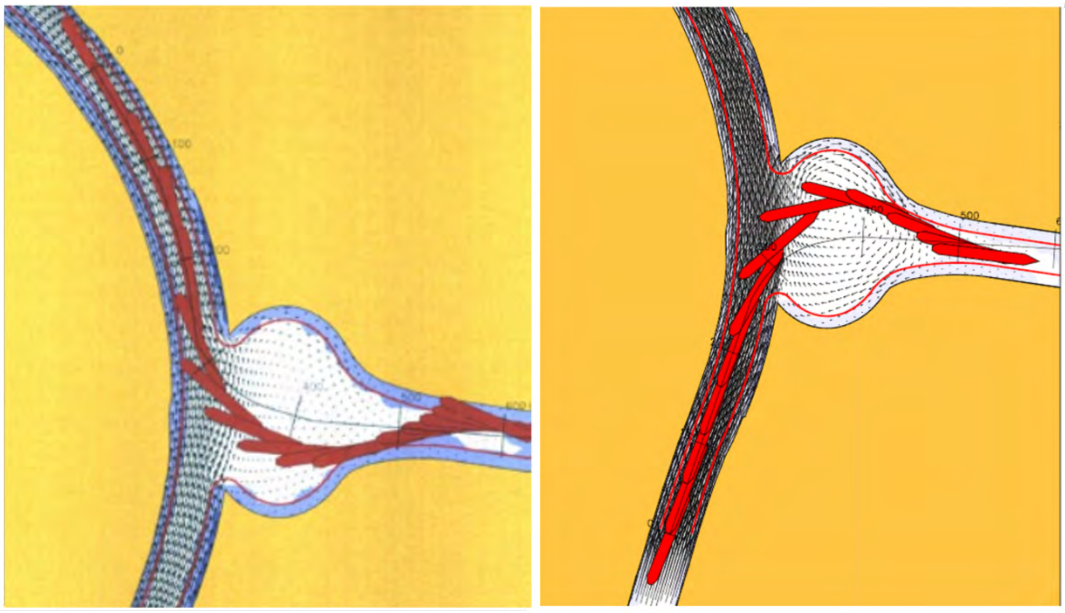


Figure 2.58: Simulated entrance manoeuvres of vessels sailing upstream (left) and downstream (right) (source: Euro-Hafen Emsland-Mitte, Delft Hydraulics, report Q4072, 2006).

Access channels not equipped with a Thijsse-egg are often built under a sharp angle with the river axis, such that the channel mouth is facing downstream (Figure 2.59). The principal objective is to prevent sedimentation in the centre of the channel mouth, in order to maintain sufficient navigable depth. For ports along a river having a basin length of at least 1000 m or more than 10 times the length of the design vessel, entering head-on and turning inside the port is preferable to entering backwards. Shape and angle of the entrance then depend on the sailing direction of most of the vessels, but generally the entrance will be perpendicular to the waterway axis.

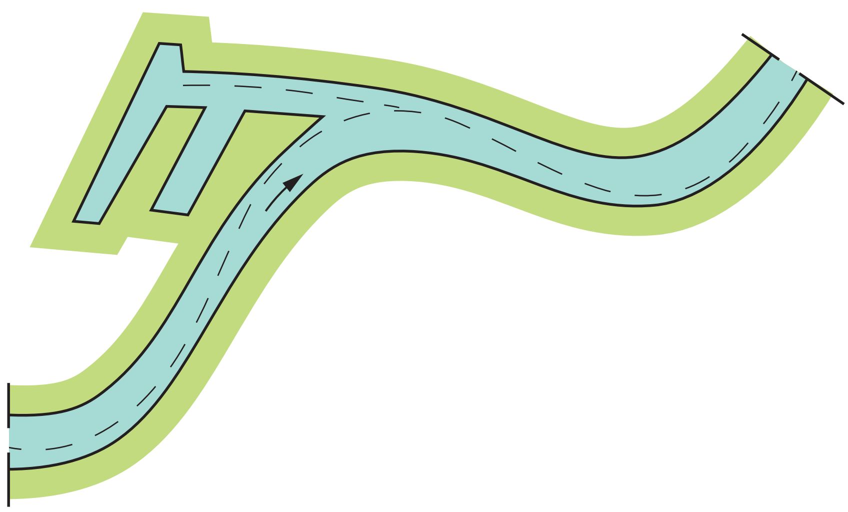


Figure 2.59: Oblique connection between a river and a port entrance (by TU Delft – Ports and Waterways licenced under CC BY-NC-SA 4.0).

Irrespective of how the access channel is connected to main fairway, safety requires that the helmsman of a vessel leaving the access channel has sufficient line of sight over the fairway and vice versa. Figure 2.60 shows what this means in terms of lines of free sight. Depending on the CEMT class and the sailing direction relative to the current direction, the line of site should be 3 to 5 times the design vessel length, with a maximum of 600 m.

In addition, it is necessary to place sufficient visual guiding along the waterway to ensure a timely start of the entrance manoeuvre, to respond to unexpected situations, and keep the ship under control in the changing current field. See for more information Richtlijnen Vaarwegen (RVW, 2020).

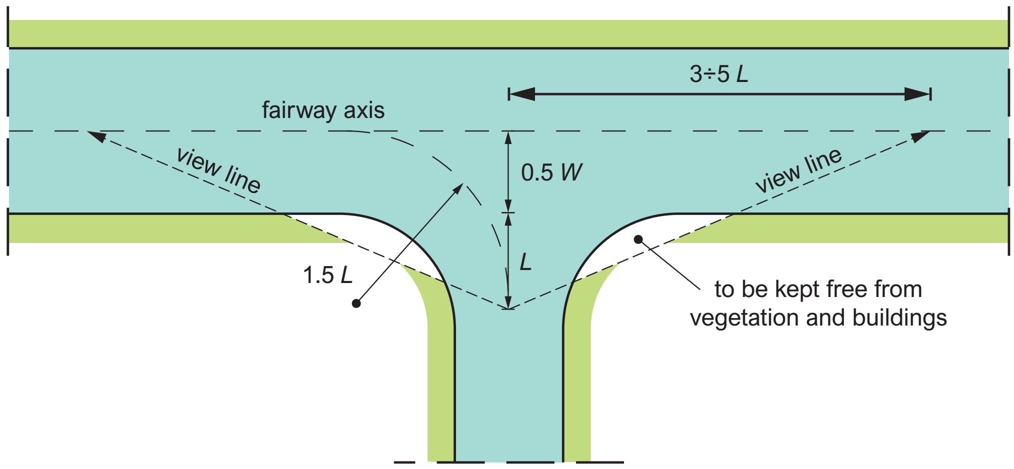


Figure 2.60: Unobstructed view lines at connections (by TU Delft – Ports and Waterways licenced under CC BY-NC-SA 4.0).

2.4.3 Port water areas

When designing a river port, a few points have to be kept in mind (RVW, 2020):

- in the river, the water level set-up induced by the port should be as small as possible,
- sedimentation, in the port as well as in the river, should be kept at a minimum,
- changes in the current pattern should be avoided and cross-current should be limited.

Access channel

Dimensional requirements to access channels of inland ports depend on the type of waterway (RVW, 2020). In general:

- the entrance should be:
  - if on a canal: as wide as possible, such that the opening enables ships to make the turn into the access channel;
  - if on a river: as narrow as possible, in order to limit sedimentation and changes in the flow pattern in the river.
- the channel inside the mouth should be:
  - if on a canal: short, as the wide entrance and the absence of a current allow a ship to sail in slowly and in control;
  - if on a river: long, as a ship sailing downstream enters at a relatively high speed due to the current and needs some distance to stop and line up.

These design principles can be used for waterways wider than 0.8 times the length of the design vessel, where the vessel can perform a large part of its turning manoeuvre at the river. At smaller waterways, a larger entrance width is required, about the length of the design vessel. Simulations will often be necessary, where sailing into the port in downstream direction will be the normative condition.

In order to limit sedimentation in the port access, it is recommended to construct a guide wall at the upstream side of the port access (unless the current changes direction, like in tidal rivers). Such a structure directs the flow towards the river axis. Moreover, it provides a clear boundary to the skippers.

The above principles result in an entrance width of about 4 times the beam of the reference vessel. For high current velocities in the river a larger width may be necessary. This can be determined in a combined hydromorphological and nautical study.

The depth should be the same as in the main fairway, with a minimum UKC of 1 m. It is important to consider expected future large-scale bed level changes, such as the incision of the Rhine branches in the Netherlands.

Turning basin

Turning basins (minimum diameter 1.2 L_s) enable vessels to manoeuvre in the vicinity of a quay along a waterway or inside a port basin. In the former case, the turning basin may cover part of the main fairway, provided that this is not too busy. RVW (2020) states that on waterways with more than 15,000 passages of commercial vessels per year the turning vessel must stay outside the fairway lane at the opposite side.

Port basin

Dimensional requirements for the port basin are not essentially different from those in a sea port, though at a different scale. The quay length for a single vessel is 1.1 to 1.2 times the length of the design vessel. If more vessels are to be berthed side by side, 1.2 L_s is required per vessel. A space-efficient basin design is obtained with 2 moored vessels next to each other, at each side. This requires a basin width of 7 times the beam of the design vessel.

The depth in the basin should be the same as in the main fairway. A minimum UKC of 1 m is recommendable, in view of the erosive force exerted by thruster and main propeller jets.

Quays and wharves

Quays and wharves are parallel mooring locations along the waterway. On busy waterways with more than 30,000 passages/year or on waterways for CEMT Class V or higher, these moorings should be avoided, as regulations force passing vessels to reduce speed, in order to avoid damage to the moored vessel(s). Particular measures for a quay or wharf are not necessary, except a safety area between the berth and the shipping lane. RVW (2020) gives further details.

Vessels should have the opportunity to turn, if necessary, within 1000 m from the quay or wharf. On rivers vessels can make use of groyne fields and port connections to turn.

Overnight ports, recreational ports, et cetera

RVW (2020) offers special guidance for various other types of ports, including provisions such as a car boarding facility, and moorings for vessels carrying hazardous goods (blue cone vessels). It also gives a procedure to determine the required capacity.

2.5 Manoeuvring simulators, capacity models and nautical safety analysis

In the conceptual and final design stages of port access channels, port water areas and inland waterways simulation and capacity models as well as a nautical safety analyses will be necessary. Specific situations are often too complex to rely on analytical design rules only. In that case, the first estimate of the required layout will be followed by ship manoeuvring and capacity simulations. They give insight into the inherent possibilities and/or restrictions infrastructure, environmental conditions and vessel types, including the role of tugs and the effects of additional manoeuvring devices such as bow and stern thrusters. Based on the insight gained, adaptations of the infrastructure design (channel layout, manoeuvring basin and terminal layout) and/or the admittance policy can be proposed. In the initial stage of the design a fast-time simulation program will be applied; in the final stage a study on a real-time simulator may follow. Moreover, nautical safety must be studied qualitatively or quantitatively.

2.5.1 Simulation models

Manoeuvring simulators The use of Fast-Time Simulators FastTime Simulators (FTS) in the early stages of a design and the use of Real Time Simulators Real Time Simulator (RTS) in the final design stage provides insight into the behaviour of one particular vessel in the proposed layout of the port water areas, the access channel or the inland waterway. RTS models can also be used for operational applications, such as training of captains and pilots, or to find solutions for problems encountered.

SHIPMA is the fast-time manoeuvring simulator used in the Netherlands. The program is a joint development of MARIN's nautical centre MSCN and Delft Hydraulics (now Deltares). The combined expertise has led to a fit-for-purpose tool to simulate the manoeuvring behaviour of vessels in ports and waterways. In SHIPMA, a vessel is steered by a track-following autopilot which is capable to perform typical manoeuvres like turning and berthing. All hydrodynamic effects are included: shallow water, bank effects, currents, wind and waves. Moreover, tugs can be implemented. One vessel is simulated and the simulation allows to compare results of different simulations on technical and physical aspects. The output gives information on track, position, course, course deviation, distance to desired track, rudder angle. Figure 2.61 shows an example of a vessel's track when entering a canal.

Another possibility is to use an RTS. In principle, these simulators are based on the same principle as an FTS, but the manoeuvres are carried out by pilots or skippers located in a ship's steering house with all the equipment present as in a real steering house. Even the view out of the windows looks natural since this is based on the real situation Figure 2.61. The effect of a human navigator is the main difference from an FTS. Figure 2.61 shows a typical result of an RTS simulator study.

RTS simulators are used not only for final designs, but also for training purposes. Obviously, the costs of using an RTS are significantly higher than those of an FTS.

Figure 2.61: View from a simulator bridge during an encounter situation (images by MARIN are licenced under CC BY-NC-SA 4.0).

Capacity models Apart from simulating manoeuvres it is important to determine the capacity of a waterway, port, or terminal. These type of models simulate the nautical traffic during a certain period, in order to determine not only the capacity, but also peak moments, waiting times, et cetera. In general, there are two ways to determine the various capacity aspects, viz.:

1. analytical models
2. simulation models

Examples of analytical models are the Kooman method for lock performance (Kooman and De Bruijn, 1975), yielding the waiting and passing times of locks, and queuing theory (see Part IV – Section 2.4 for waiting times at ports.

The second type of capacity models are simulation models. In the Netherlands Rijkswaterstaat uses the models BIVAS, SIMDAS and SIVAK. BIVAS computes traffic volumes and intensity-capacity ratios for the Dutch waterway network. SIMDAS and SIVAK focus on the capacity of a certain reach of an open waterway (ship-ship interaction) and near an infrastructure (ship-infrastructure), respectively. BIVAS, SIMDAS and SIVAK are discussed in more detail in (see Part IV – Section 2.6.1). Examples of studies carried out are: Verschuren (2020) studied the effect of low discharges at the river Rhine on the navigation with SIMDAS, and (Van Adrichem, 2020) studied the optimization of lock scheduling with SIVAK.

Recently, OpenTNSim has been developed, of which an example is given in Part IV – Section 2.6.1. This model simulates (part of) a transport network.

Often analytical models suffice, but if the system becomes too complex simulation models have to be used. This can be the case, for instance, if:

- The sailing time from the anchorage to the quay cannot be neglected in relation to the servicing time;
- The number of berths is dependent on the length of the ships, and
- The tidal conditions affect the functioning of the system, etc.

2.5.2 Nautical safety analysis

Quantification of the nautical safety in ports and waterways is becoming more and more important. Safety can become critical before the theoretical capacity is reached. Up till recently, a qualitative assessment was made very often using a Formal Safety Analysis (FSA). However, the present trend is to use a quantitative analysis via simulation models.

Qualitative analysis The International Maritime Organization (IMO) recommends the FSA method in order to address the nautical safety. The methodology consists of five steps:

1. identification of hazards
2. risk assessment
3. risk control options
4. cost-benefit assessment
5. decision-making recommendations

Obviously, Steps 2 and 3 are very important. In Step 2 the probability and impact estimation per hazard must be determined. Step 3 deals with mitigating measures to reduce the probability and the impact. A part of the method is a questionnaire for retrieving expert judgement on hazards and an expert session to discuss the hazards, the mitigating measures and their effects. Figure 2.62 shows the FSA methodology.

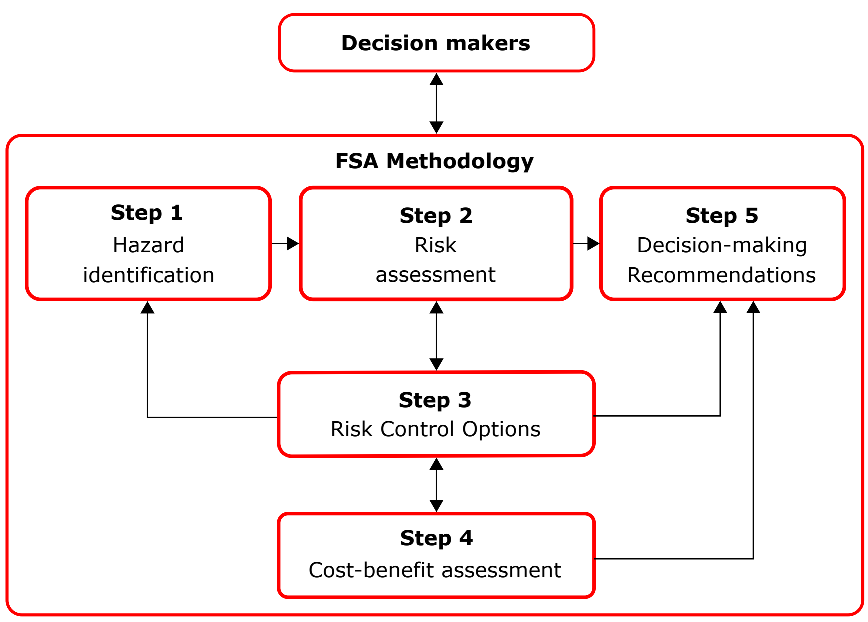


Figure 2.62: Methodology of the Formal Safety Analysis (reworked from IMO, 2018, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Quantitative analysis An early example of a quantitative method is SHIPRISK developed at the TU Delft by Groenveld. It was used to determine the risks during construction of Maasvlakte 2. A limitation of SHIPRISK and comparable models is that the vessels follow a predetermined fixed course. To overcome this limitation, recent research has focused on methods to simulate the real behaviour of vessels, such as manoeuvres during overtaking and encounters in various conditions with respect to wind, sight and current. Automatic Identification System (AIS)-data of the Nieuwe Waterweg provided statistical input.

So far, it has resulted in two validated methods:

1. Application of Artificial Force Field: the behaviour of each vessel is determined by forces which are a function of the distance to the bank, other vessels, bridge piers, et cetera (Xiao, 2014).
2. Optimal Control Approach: the vessel route is calculated by minimizing the energy use (Shu, 2019).

However, a lot of work still has to be done to derive operational models.

MARIN developed a quantitative analysis based on:

- traffic analysis
- SAMSON

The traffic analysis deals with where and how vessels actually sail. Obviously, AIS plays an important role. Based on that information density maps and track plots can be made. The method includes an intensity analysis and the determination of a route structure, finally resulting in a traffic database for the simulation model SAMSON (Safety Assessment Model for Shipping and Offshore on the North Sea). This model provides the opportunity to determine ship-ship and ship-object interactions. Figure 2.63 shows an example of track plots for a windfarm in the IJsselmeer.

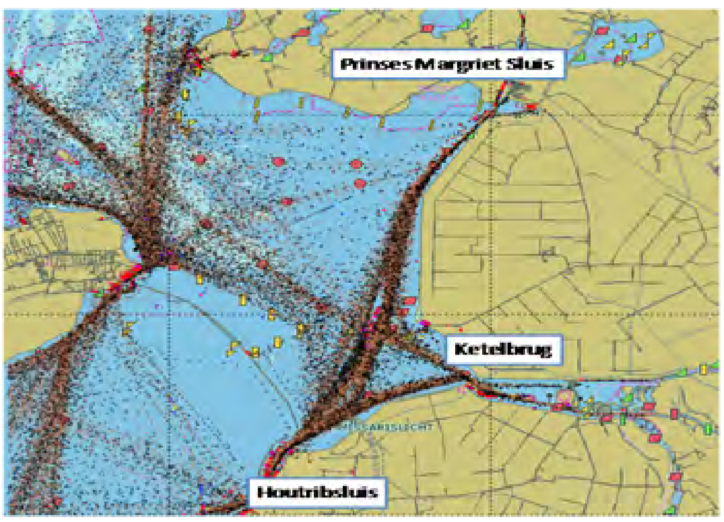


Figure 2.63: Track plots of ships on the IJsselmeer for a risk analysis of collisions between ships and wind mills of an offshore windfarm (image by MARIN is licenced under CC BY-NC-SA 4.0).

3 Waterway elements

[1]Waterways generally consist of various elements, such as river reaches, canal sections, locks, weirs and bridge passages. In this chapter we will focus on the design of locks and bridges. An important source of information for this chapter - as far as the Dutch waterways are concerned - are Rijkswaterstaat's Waterway Guidelines 2020 (RVW, 2020, in Dutch; latest English version: 2020). In 2019 PIANC issued its 'Design Guidelines for Inland Waterway Dimensions' (InCOM WG Report 141 PIANC, 2019a), based on the national guidelines of the member states. This does not conflict with the Rijkswaterstaat guidelines. Other relevant manuals are PIANC Report 106 'Innovations in navigation lock design' (PIANC, 2009) and PIANC Report 155 'Ship behaviour in locks and lock approaches' (PIANC, 2014e). In this chapter, we will focus on the situation in the Netherlands, as an illustration of how one can go about the design and operation of these waterway elements.

3.1 Functional design of locks

Sometimes it is necessary to separate bodies of water along a waterway by a structure. This can be the case if

- the water level in a certain part has to be set up for navigability, like in a canalised river;
- the water level at one side has to be set up for storage, like in the case of a reservoir;
- the water level at one side has to remain constant, while at the other side it may vary; this is the case, for instance, where a canal meets a river, but also at a transition between tidal and non-tidal waters, or at a flood defence dam or a storm surge barrier;
- the water is saline at one side and fresh at the other, like in the case of sea locks.

Such a separating structure may be a weir, a dam or a storm surge barrier provided with a lock to enable navigation, but it may also be the lock, itself. A structure can be provided with a single lock, or with a system of locks (Figure 3.1).

Figure 3.1: Multiple-lock systems. Left: Sea Locks (major lock as projected), IJmuiden, Netherlands (https://beeldbank.rws.nl, Rijkswaterstaat, by: Harry van Reeken); right: Three Gorges Project, China (Three Gorges Locks by RThiele is licenced under CC BY-SA 3.0).

Apart from the different separation functions mentioned above, locks may also be distinguished by vessel type:

- locks for commercial sea-going vessels, like the locks in the Panama Canal (Part III – Chapter 1), or those in the North Sea Canal at IJmuiden (Figure 3.1, left),
- locks for commercial inland vessels, like the locks in the river Maas (Figure 3.2),

[1]This chapter made use of '*Capacities of Inland Waterways*' (Groenveld et al., 2006), lecture notes for the Ports and Waterways course CIE5306 at TU Delft.

- locks for recreational vessels, like the lock between the river IJssel and the Reevediep bypass towards Lake IJssel (Figure 3.3, left),
- locks for mixed commercial and recreational vessels (Figure 3.3, right).

Figure 3.2: Locks at Lith for commercial traffic at the Maas river (image by https://beeldbank.rws.nl, Rijkswaterstaat, by: Bart van Eyck).

Figure 3.3: Locks for recreational (left) and mixed (right) traffic (Sluiskolk zeilboot pleziervaart beroepsvaart and Sluiskolk beroepsvaart recreatievaart by https://beeldbank.rws.nl, Rijkswaterstaat).

Lock passage is a time-consuming operation which may limit the capacity of a waterway. Therefore, capacity is an important criterion for lock design. In order to determine this capacity, the lock passage process needs to be analysed. We will describe this analysis before going into the functional and dimensional requirements of the various elements.

3.1.1 Lock operation

One perspective of the locking cycle is that of the lock operator, who will focus on the following points successively (RWS, 1973):

1. the stern of the last ship of the previous locking cycle passes the lock sill on exit,
2. the stern of the first ship of the new cycle passes the lock sill while entering the lock chamber,
3. the stern of the last ship of this cycle passes the lock sill, so door closing can begin,
4. the doors are closed and the water level in the lock chamber can be adjusted to that at the exit side,
5. the water level in the chamber is (almost) adjusted and the exit doors can be opened,
6. the exit doors are open and the stern of the first ship leaving passes the lock sill,
7. the stern of the last ship leaving passes the lock sill and the operation in opposite direction can begin when this ship has passed the waiting area.

Figure 3.4 summarizes this in a schematic diagram.

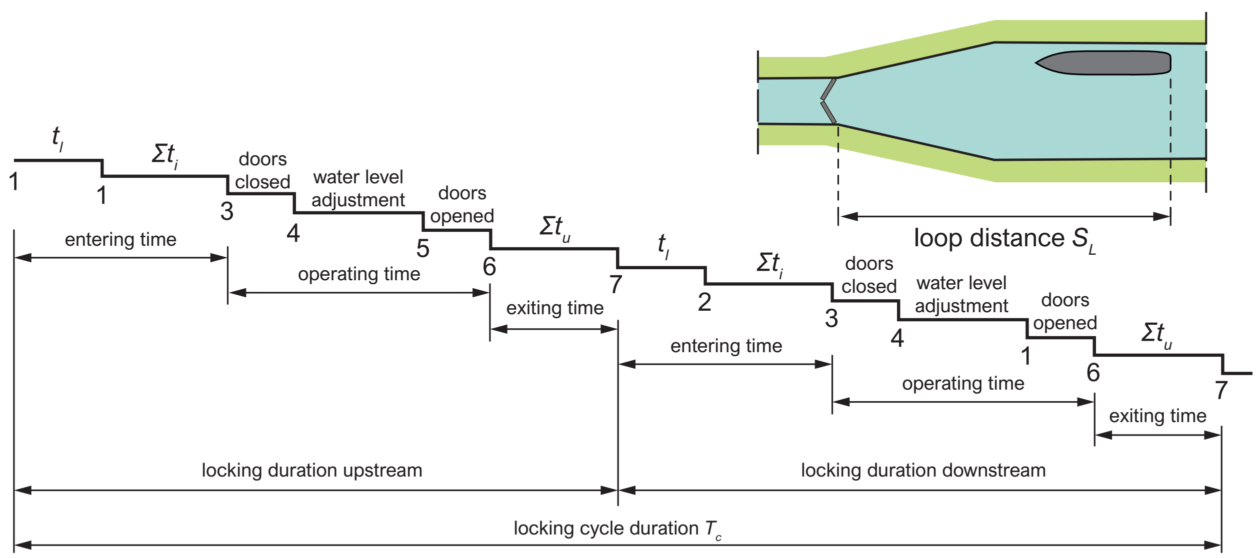


Figure 3.4: Schematic of a locking cycle (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The total duration of the locking cycle follows from:

$$T_c = \left(t_l + \sum_{i=2}^{nu} t_i + T_{\text{close}} + T_{\text{waterlevel}} + T_{\text{open}} + \sum_{u=1}^{nu} t_u \right)_{\text{up}} + \left(t_l + \sum_{i=2}^{nd} t_i + T_{\text{close}} + T_{\text{waterlevel}} + T_{\text{open}} + \sum_{u=1}^{nd} t_u \right)_{\text{down}} \quad (3.1)$$

Where:

T_c	=	the total duration of the locking cycle (upstream + downstream)
nu	=	number of vessels to be locked through in the upstream phase,
nd	=	number of vessels to be locked through in the downstream phase,
t_l	=	the so-called loop time, i.e the time between the moment the stern of the last ship leaves the lock and the time the stern of the first ship enters the lock,
t_i	=	the entering time of vessel i,
t_u	=	the exiting time of vessel u,
T_{close}	=	the time needed to close the gate or doors,

$T_{\text{waterlevel}}$	=	the time needed to adjust the water level in the lock chamber,
T_{open}	=	the time needed to open the gate or doors.

Note that the entrance of the first vessel is counted when its stern passes the lock sill, in line with a general agreement to count vessels by the stern. It means that this vessel's approach to the lock and its lock entrance are added to the loop time, in contrast to all following vessels. Consequently, the counter i of the t_i summations in Equation 3.1 starts at $i = 2$.

Figure 3.4 shows a number of other time spans:

entering time:

$$t_l + \sum_{i=2}^{n} t_i \tag{3.2}$$

operating time:

$$T_{\text{operation}} = T_{\text{close}} + T_{\text{waterlevel}} + T_{\text{open}} \tag{3.3}$$

exiting time:

$$\sum_{u=1}^{n} t_u \tag{3.4}$$

Note that if the lock operates only in one direction, the formula for the total locking cycle becomes slightly different, because after the vessels have left the lock, the water level in the chamber has to be restored before the next cycle can begin:

$$T_c = t_l + \sum_{i=2}^{n} t_i + T_{\text{operation}} + \sum_{u=1}^{n} t_u + T_{\text{operation}} \tag{3.5}$$

The lock capacity is defined as the maximum quantity of traffic that can be locked through per unit time if the lock is continuously in operation. It can be expressed in numbers of vessels, in dead-weight carrying capacity, or otherwise. When expressed in numbers of ships, it is given by

$$C_s = 2n_{max}/T_c \tag{3.6}$$

in which n_{max} is the average number of vessels per locking operation in a large number of operations with a full chamber. This can be translated to tonnage per unit time via

$$C_T = C_s \overline{T}_{dw} \tag{3.7}$$

in which $\overline{T}_{dw}$ is the average dead-weight carrying capacity per vessel.

Note, however, that this capacity definition refers to full capacity operations in both directions. If traffic is mainly in one direction, one may define the capacity in that direction by

$$C_s = n_{max}/T_c \tag{3.8}$$

Note that the total cycle duration T_c is still in the denominator of this formula. This means that if the traffic in the other direction becomes less and T_c decreases accordingly, the lock capacity increases, until it reaches its maximum if there is no traffic in the other direction and Equation 3.5 applies to T_c.

From the point of view of a passing vessel's skipper, the lock cycle can be separated into the following phases (see Figure 3.5):

(0 → 1)	approaching the lock at cruising speed,
(1 → 2)	arrival at the upstream lock area, slowing down to full stop and mooring in the waiting area,
(2 → 3)	waiting until in lay-by the lock can be entered,
(3)	once the last ship leaving the lock has passed: unmooring and marshalling for lock entry,
(3 → 4)	speeding up, entering the lock chamber,
(4 → 5)	once in the lock chamber: slowing down to full stop and mooring in the lock chamber,
(6 → 7)	once the lock chamber is full (or all waiting vessels are in): door closing and water level adjustment in the lock chamber,
(7 → 8)	other door opening and unmooring,
(8 → 9)	once the door is open speeding up and leaving the lock chamber,
(9)	ship stern passes the exit lock sill,
(9 → 10)	leaving the other lock area and continuing the journey at cruising speed.

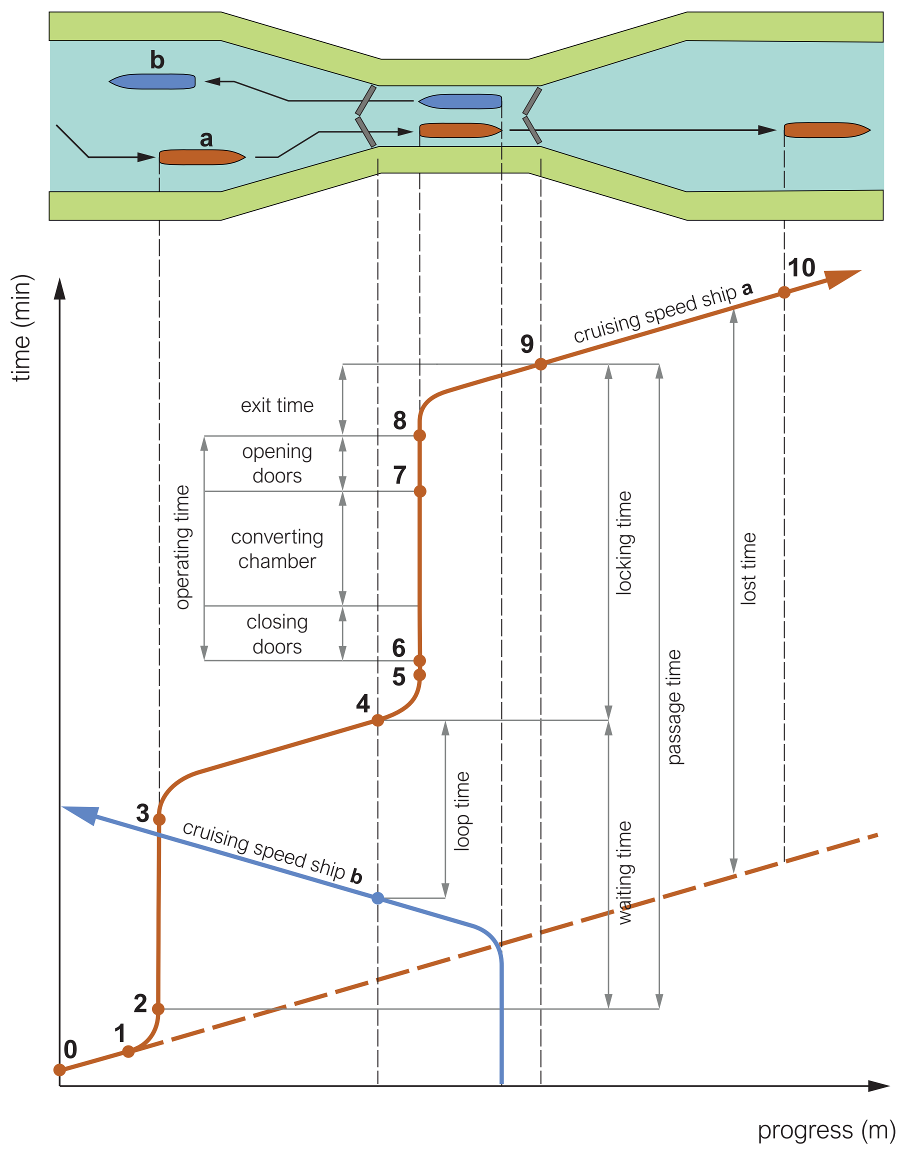


Figure 3.5: Tracking diagram for single vessel (red) passing a lock (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The skipper will experience the lock passage as an inhibitory factor of his journey and will be inclined to compare the gross lock passage time with the time he would have needed if the lock would not have been there (and would not have been necessary). Therefore, the lost time of an individual vessel, t_{lost}, is its total lock passage time $(t_w + t_s)$ minus its passage time at undisturbed cruising speed:

$$t_{lost} = t_w + t_s - L_{\text{lock}}/V_s \tag{3.9}$$

where:

t_w	= waiting time,
t_s	= locking time,
L_{lock}	= lock length (entry area plus the lock chamber),
V_s	= undisturbed vessel cruising speed.

The total waiting time may range from zero to a number of locking cycles in case of heavy traffic:

$$t_w = kT_c + t_{wr} \qquad (k = 0, 1, 2, \cdots) \tag{3.10}$$

in which t_{wr} is the remaining waiting time after the last cycle before entering has been completed, and kT_c is referred to as holding time ("overligtijd" in Dutch).

The opening and closing times of the lock gates depend on the type of gate and the width of the lock. Table 3.1 gives examples of observed operating times for three types of electrically operated gates.

Gate type	**Chamber width (m)**	**Closing time T_{close} (min)**	**Opening time T_{open} (min)**	**Total gate operation time (min)**
Rolling gate	12	1.2	0.7	1.9
Vertical lift gate	14 – 18	3.0 – 3.3	2.0 – 2.3	5.0 – 5.6
Mitre gate	16 – 24	1.3 – 2.5	1.2 – 2.6	2.5 – 4.1

Table 3.1: Gate operating times (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The time needed for water level adjustment depends on the system used for filling and emptying the lock chamber. This will be discussed in Chapter 4. An important aspect is the ship motion during filling and emptying. When filling the chamber, the decelerating entry flow may be quite turbulent. If the chamber is filled or emptied from one end, this may give rise to translation waves and density currents travelling up and down the chamber, reflecting against the gates (Figure 3.6).

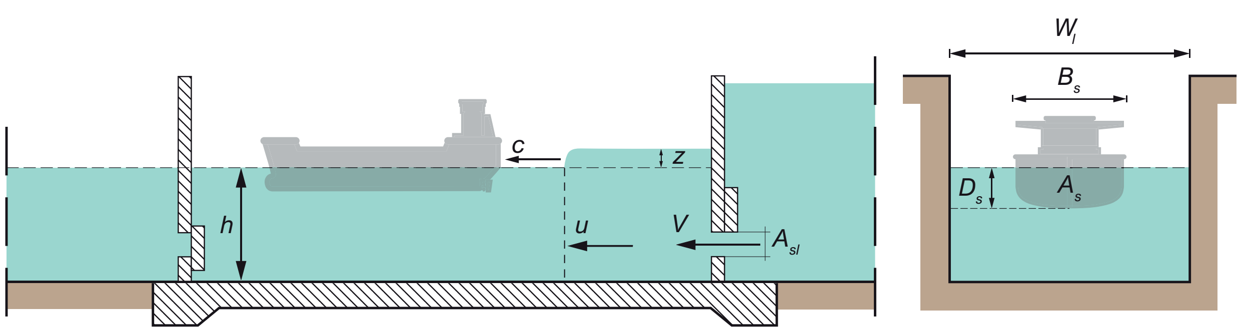


Figure 3.6: Translation wave in a lock chamber (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The vessels moored in the chamber will respond to these effects, yielding large time-varying forces in hawsers and bollards (Figure 3.7). In order to avoid excessive hawser forces, only one hawser is tightened, whereas the other one is allowed to slip, so as to absorb the vessel's kinetic energy. In Part IV – Section 4.2 we describe how hawser and bollard forces can be estimated.

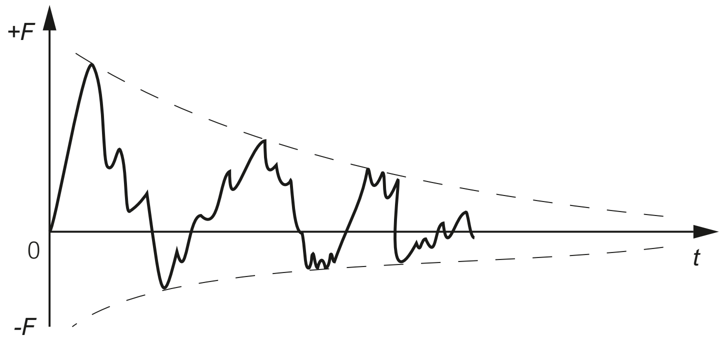


Figure 3.7: Hawser forces exerted by a vessel in a lock chamber (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

3.1.2 Entry and exit times

The entry (following the first vessel entering) and exit times of vessels are determined on the basis of a large number of field measurements, as a theoretical approach is hardly possible. In a major study in the Netherlands (RWS, 1973) entry and exit times were determined in a large number of locks (16 lock complexes and 23 lock chambers). The data show a considerable scatter, particularly due to the influence of human behaviour and differences in manoeuvrability of the vessels.

Figure 3.8 gives two practical examples. The top panel refers to the entry following times (t_i) of laden motor vessels in the *Hartelsluizen* (chamber dimensions 24 × 280 m^2 and 12 × 120 m^2). The bottom panel refers to the exit following times (t_u) of laden motor vessels at the *Volkeraksluizen* (chamber dimensions 24 × 325 m^2).

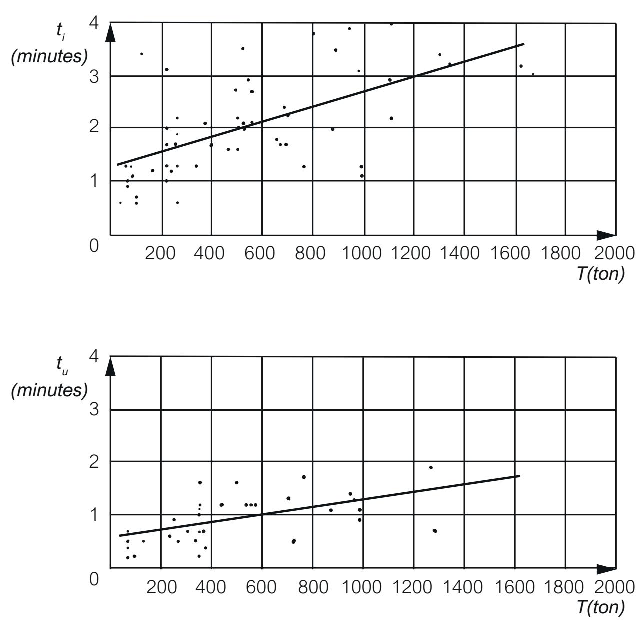


Figure 3.8: Examples of entry and exit times as function of the carrying capacity of a vessel (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The data for motor vessels led to the following conclusions:

1. The entry and exit times increase with the vessel's load capacity.
2. The entry and exit times of unloaded vessels are significantly shorter than for loaded ones.
3. The entry and exit times of a ship with a specific load capacity clearly increases as the cross-sectional area of the lock chamber ($A_{lock} = W_l\ h$) decreases.
4. The entry and exit (following) times for towed barges are clearly longer than for motor vessels or push-barge convoys.
5. The entry and exit times are unfavourably influenced by chamber shapes that deviate from a rectangular profile (e.g. a so-called 'green' chamber) and by 'blindly' situated waiting areas (e.g. in bends).
6. The loop time is directly dependent on the so-called loop distance S_l (see Figure 3.4).

The resistance when entering or leaving a lock is taken into account as a function of the blockage coefficient A_s/A_{lock}.

In the transition between the lock approach and the relatively narrow lock a ship has to adapt to changing hydrodynamics. A sudden transition in width causes the following phenomena:

- an increase of the return current and the water level depresssion,
- a positive translation wave entering the lock chamber;
- a negative translation wave propagating into the lock approach area.

The higher the vessel's speed and the larger the blockage coefficient, the stronger these phenomena are.

As a result of these phenomena, a vessel's speed during the actual lock entry may be rather irregular (Figure 3.9). In practice, however, it appears that with a blockage coefficient less than 0.4 there is generally little cause for concern.

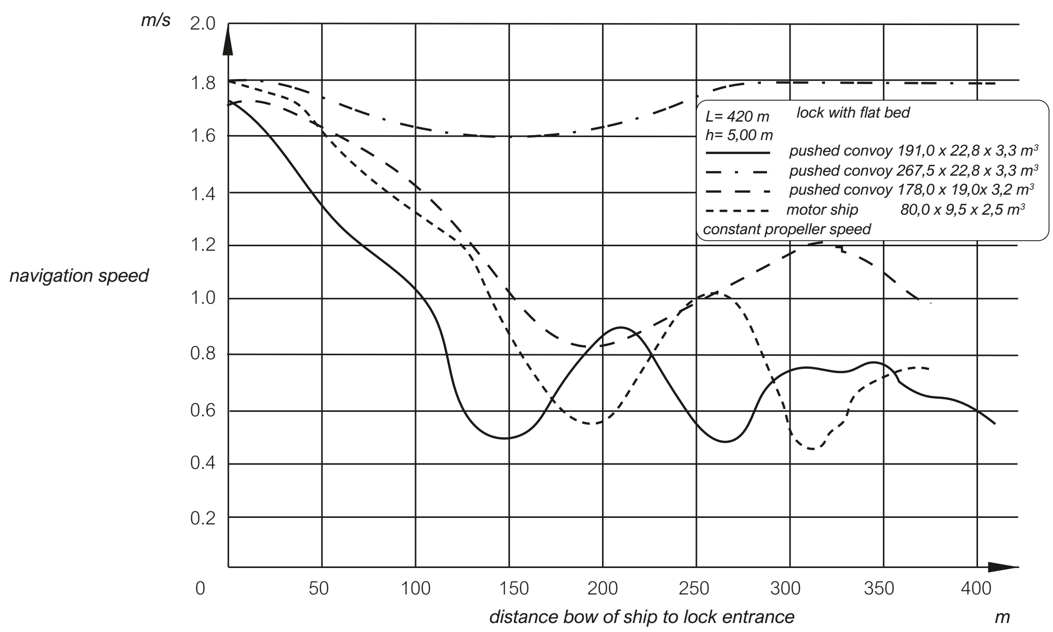


Figure 3.9: Variation of navigation speed when entering a lock (Kooman, 1973) (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Another problem applies to loaded push-barge convoys in inland locks and the largest sea-going vessels in maritime locks (blockage coefficient 0.7 to 0.8). Their initial speed (V_s) may not be too large, in order to keep the translation wave created by them from causing damage to the closed gates the first time it rebounds.

Figure 3.10 shows the relationship between the blockage coefficient and the entry and exit times for loaded and unloaded standard ships. The figure was determined for locks with a head width equal to the chamber width and a well-arranged situation. Corrections are needed in case of deviations from these conditions, such as towed barges, different lock shapes, wind hindrance and unfavourably arranged situations. Note that the standards used here are *not* the CEMT– or RWS 2010 standards.

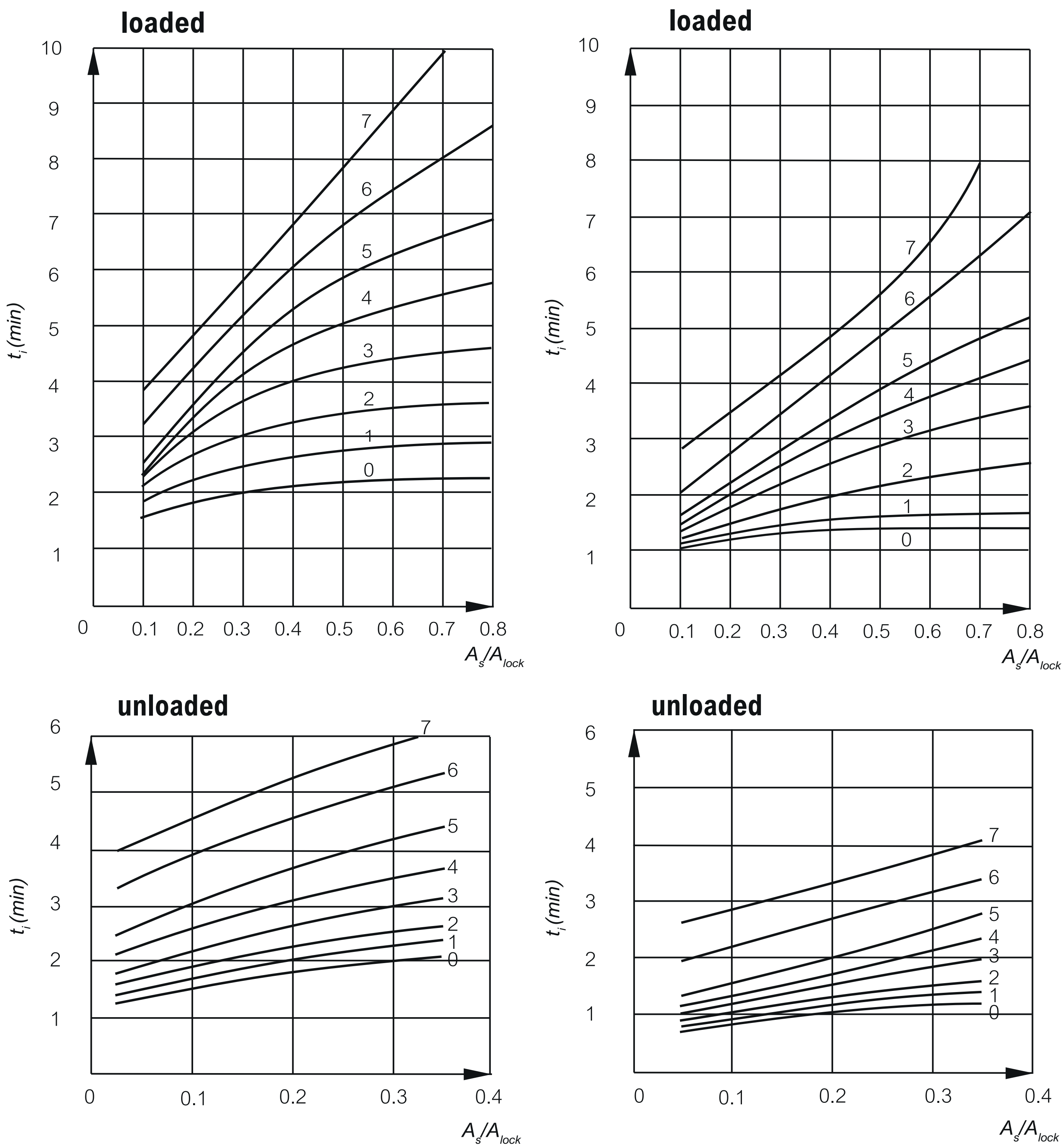


Figure 3.10: Entry and exit times for loaded and unloaded standard vessels (for codes see table) (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Although out of date as such (Kooman and De Bruijn, 1975), the values from Figure 3.10 can be used as input to demonstrate how lock dimensions and capacities can be calculated. The Dutch Commissie Vaarweg Beheerders (CVB, Commission of Fairway Managers) strongly recommends that with a large volume of traffic (> 10.000 passages per year) the necessary number of lock chambers and the minimum dimensions thereof should be determined with the aid of simulation models. For the sake of the present explanation, we will stick to the situation in the 1970s.

For a first impression one can use the average values for t_i and t_u for a given traffic mix:

$$\bar{t}_i = \sum_{s=0}^{m}(P_s \cdot t_{is}) \tag{3.11}$$

and

$$\bar{t}_u = \sum_{s=0}^{m}(P_s \cdot t_{us}) \tag{3.12}$$

where P_s is the percentage of the vessel class in the traffic mix and m_{cap} is the highest occurring dead-weight capacity class; t_{is} and t_{us} are the entry and exit following time for class s, respectively.

Other input needed is the fleet composition. In 1972-1973 fleet divisions in the Netherlands were established as a function of the average carrying capacity $\overline{T}_{dw}$ of the vessel mix (Figure 3.11).

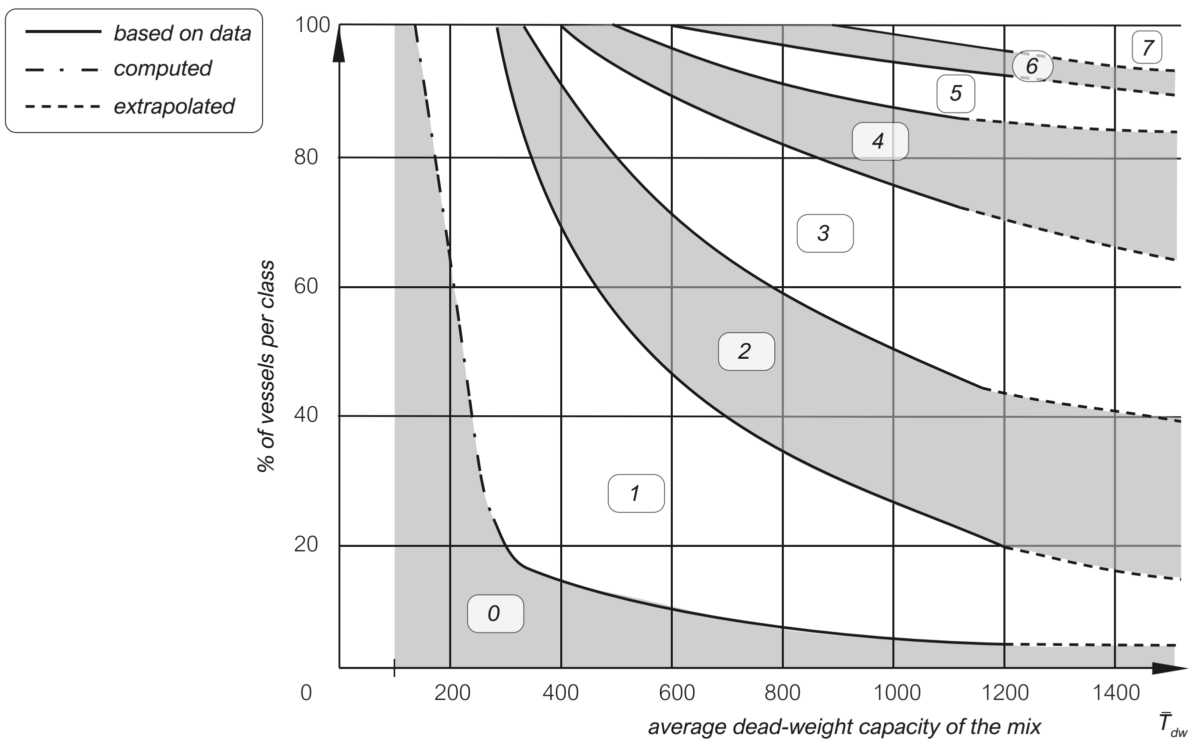


Figure 3.11: Percentage of vessels per class in a vessel mix with given $\overline{T}_{dw}$ (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Table 3.2 gives the same information in numbers. Table 3.3 gives alternative fleet compositions for channels of a lower navigability class.

In many cases this standard classification for ships was insufficient, and a more sophisticated classification had to be applied, as in the case of traffic control studies on the major rivers (see Table 3.4).

For various average dead-weight capacities ($\overline{T}_{dw}$) the average entry following times (t_i) and exit following times (t_u) are determined as a function of the area of the wet chamber cross-section (A_{lock}), using the standard frequency distribution from Table 3.2. This was done for both loaded and unloaded ships. Figure 3.12 gives the results, showing that for a given $\overline{T}_{dw}$:

$$t_{i\ (\text{loaded})} > t_{i\ (\text{unloaded})} > t_{u\ (\text{loaded})} > t_{u\ (\text{unloaded})}$$

$\overline{T}$ (ton)	Percentage of standard vessels per class							
	0	1	2	3	4	5	6	7
125	100,0	-	-	-	-	-	-	-
160	82.5	17.5	-	-	-	-	-	-
200	62.5	37.5	-	-	-	-	-	-
240	42.5	57.5	-	-	-	-	-	-
280	22.5	77.5	-	-	-	-	-	-
300	20.0	73.0	7.0	-	-	-	-	-
350	17.5	62.5	16.0	4.0	-	-	-	-
400	15.4	54.2	20.9	9.0	0.5	-	-	-
450	13.5	48.0	24.5	11.0	3.0	-	-	-
500	12.0	43.2	26.1	13.0	4.6	0.9	-	-
600	9.3	36.7	27.0	17.0	5.6	4.4	-	-
700	7.2	33.0	25.4	20.4	7.3	5.6	1.1	-
800	6.0	30.0	24.0	22.5	9.0	6.4	2.1	-
900	5.0	26.2	24.5	23.8	10.5	6.5	2.9	0.6
1000	4.5	23.0	24.7	24.3	12.5	6.5	2.9	1.6
1100	4.5	19.5	25.0	25.0	14.0	6.5	3.0	2.5
1200	4.5	16.5	24.5	26.0	15.0	7.0	3.0	3.5
1300	4.5	14.5	25.0	25.0	16.5	7.2	2.8	4.5
1400	4.5	12.5	25.0	24.5	18.0	7.0	3.0	5.5
1500	4.5	10.5	25.0	23.5	20.0	7.0	3.0	6.5

Table 3.2: Fleet composition for a given $\overline{T}_{dw}$ (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

$\overline{T}$ (ton)	Percentage of standard vessels per class							
	0	1	2	3	4	5	6	7
	A. navigability class 4							
500	12.0	42.0	27.0	13.0	6.0	-	-	-
600	8.5	32.0	31.0	17.0	11.5	-	-	-
	B. navigability class 5							
700	7.0	29.0	27.0	22.0	8.0	7.0	-	-
800	5.0	24.0	25.0	25.0	10.5	10.5	-	-
900	4.0	18.5	23.0	27.0	13.5	14.0	-	-
1000	3.0	14.0	21.0	28.0	16.0	18.0	-	-
	C. navigability class 6							
1000	3.0	22.0	24.0	26.0	11.0	8.0	6.0	-
1200	2.0	16.0	22.0	29.0	11.0	10.0	10.0	-
1400	2.0	10.0	19.0	32.0	11.0	12.0	14.0	-

Table 3.3: Fleet composition for a given $\overline{T}_{dw}$ at lower-class fairways (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Description	tonnage	category	% of weekly total	
			1972	1973
Motor cargo or motor tanker vessel	< 450	1	18.9	13.5
	450-750	2	23.9	20.9
	750-1149	3	23.4	23.5
	1150-1549	4	11.2	15.9
	1550-2549	5	3.8	3.9
	> 2550	6	0.1	0.5
Pushed convoy or pushing motor vessel	< 5000	7	4.0	3.0
Cargo or motor tanker vessel	≥ 5000	8	3.6	4.4
Single towed cargo ship, or towed tanker ship,	< 1000	9	0.4	0.4
or coupled towed ships	≥ 1000	10	3.6	1.9
Motor vessel with towed ship, or	< 1000	11	0.2	0.6
Motor vessel adjacently coupled	≥ 1000	12	0.0	1.9
Ocean-going vessel		13	1.8	1.8
Working vessel, towed object		14	0.3	0.2
Individual towing/pushing or fishing vessel		15	2.1	1.6
Passenger vessel		16	0.9	1.2
Pleasure craft		17	1.8	4.8
The weekly total observed for both navigation directions on the river Waal east of Nijmegen in the period 12 to 19 June 1972 amounted to: 3598 ships, and in the period 19 to 26 June 1973: 3562 ships.				

Table 3.4: Observed occurrence of vessels per class on the river Waal east of Nijmegen (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

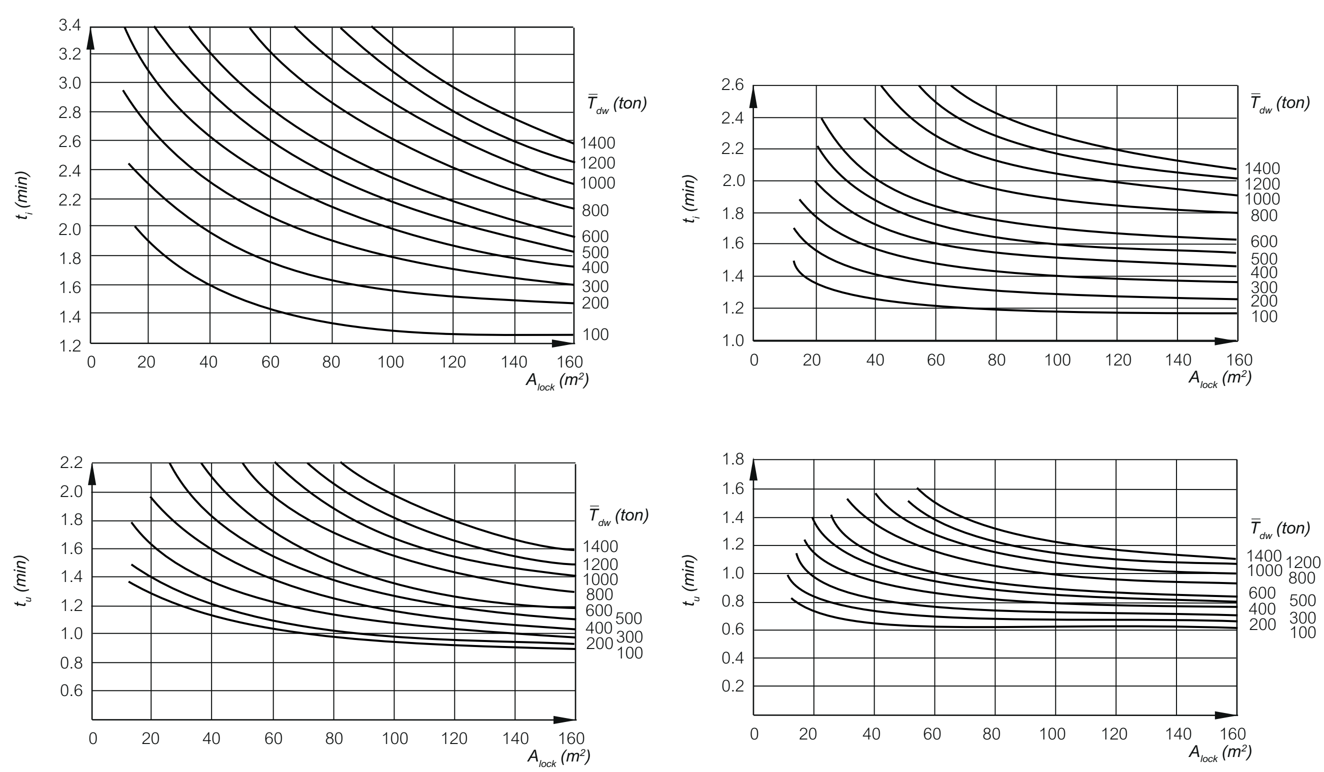


Figure 3.12: Entry and exit following times as a function of the cross-sectional area of the lock chamber (left: mix of loaded vessels, right: mix of unloaded vessels) (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

3.1.3 Loop time

As stated before, the loop time is defined as the time that elapses between the moment the last ship of the previous locking cycle leaves the lock and the moment the stern of the first ship passes the lock sill.

Just as for the individual entry and exit times, the loop time t_l is also a function of the loading status of a vessel (loaded or unloaded), the dead-weight capacity and the chamber cross-section. Furthermore, the loop time depends on the distance from the stern of the first vessel in the waiting area to the entrance gate and actually consists of two parts:

$$t_l = t_{l\ \text{(departing ship)}} + t_{l\ \text{(entering ship)}} \tag{3.13}$$

From observations it appears that $t_{l\ \text{(entering ship)}}$ is much larger than $t_{l\ \text{(departing ship)}}$. The release and acceleration of the entering vessel easily takes up the greatest part of the loop time, also because the skipper has to anticipate the slow-down and positioning in the lock chamber. This is why in practice the loop time is based on the first entering vessel only:

$$t_l = t_i(A_s/A_{lock}) + \Delta t(S_l) \tag{3.14}$$

So in this approximation the loop time is equal to the entry following time (a function of the blockage coefficient) and a correction for the extra time the first vessel requires, which is a function of the loop distance S_l as defined in Figure 3.4. Figure 3.13 gives this relationship for loaded and unloaded vessels.

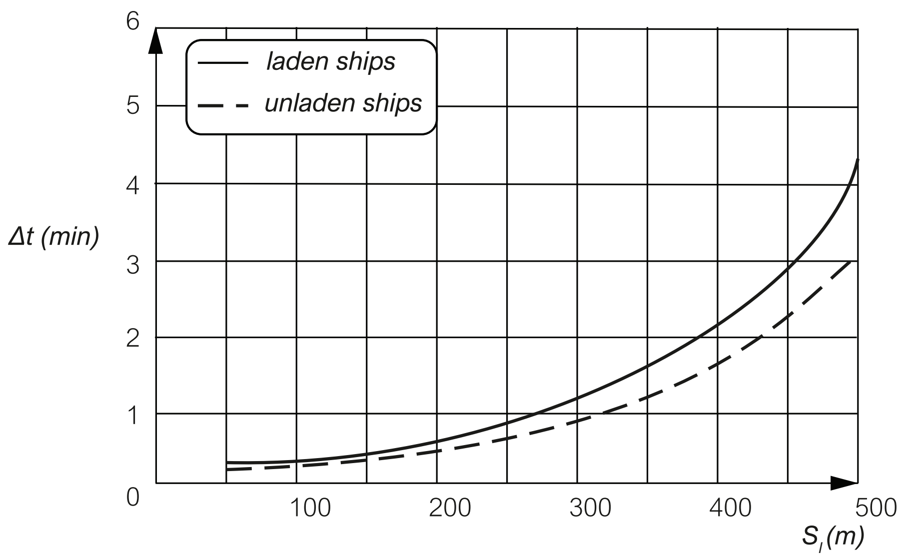


Figure 3.13: Extra time for the first vessel, as included in the loop time (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

3.1.4 Vessels in the lock chamber

It is possible to establish the maximum number of ships in the lock chamber by using a simulation on the basis of a specific fleet distribution. Some locks use a computer program to determine the optimum lock arrangement. If this is the case, lock operators try to maintain a distance between individual ships of 3% of the ship's length in the longitudinal direction and 1 to 2% of the chamber width in the transverse direction. Different criteria apply for establishing the maximum number of ships in the lock chamber of a maritime lock. Maritime vessels are, for example, always moored immediately alongside the lock walls.

Figure 3.14, Figure 3.15 and Figure 3.16 give the maximum number of ships in a lock chamber of given length and width as a function of the average dead-weight capacity. The fleet composition as a function of the average dead-weight capacity is the same as in Figure 3.11 and Table 3.2.

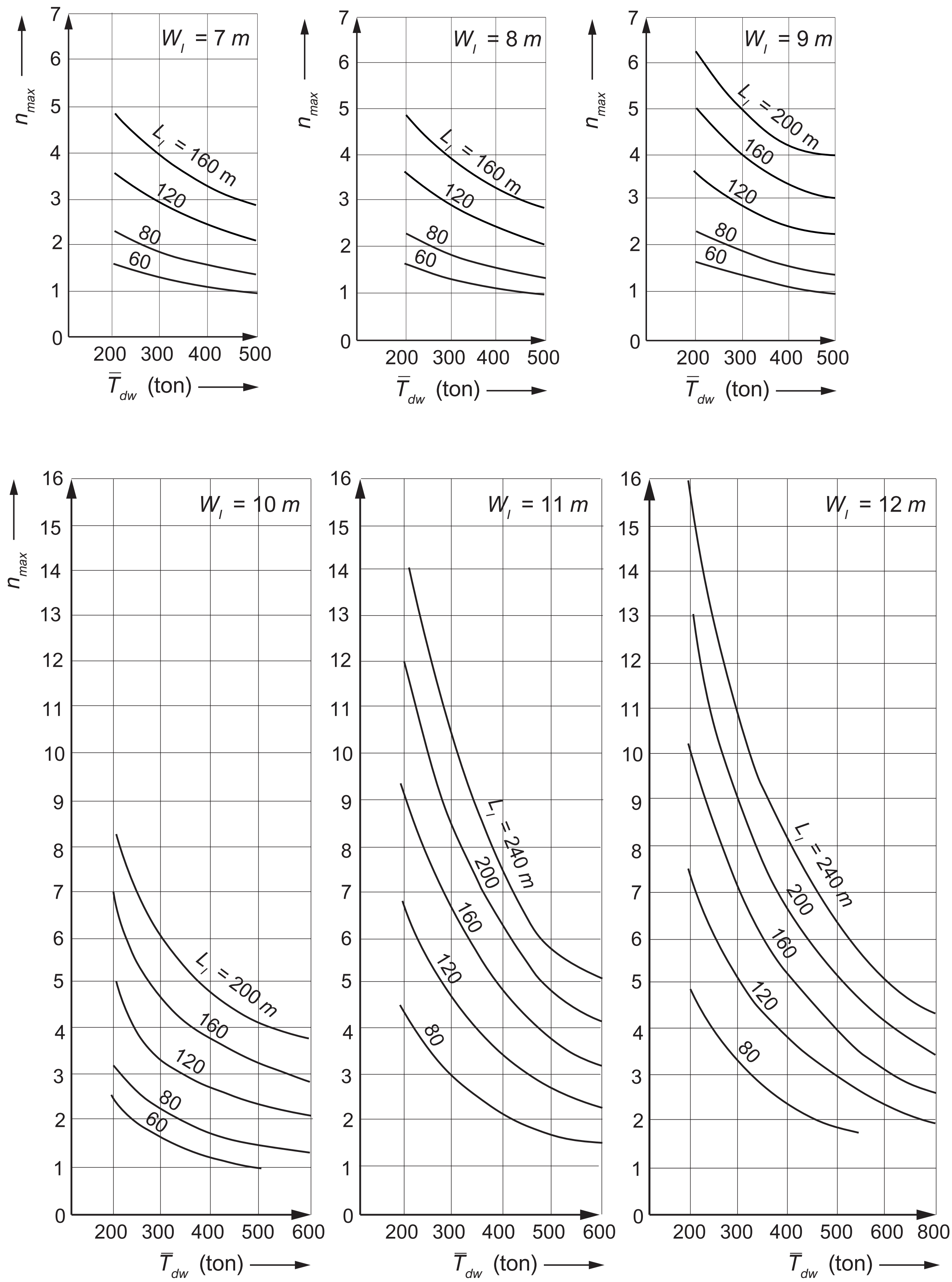


Figure 3.14: Maximum number of ships in a lock chamber, given the length and width of the chamber (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

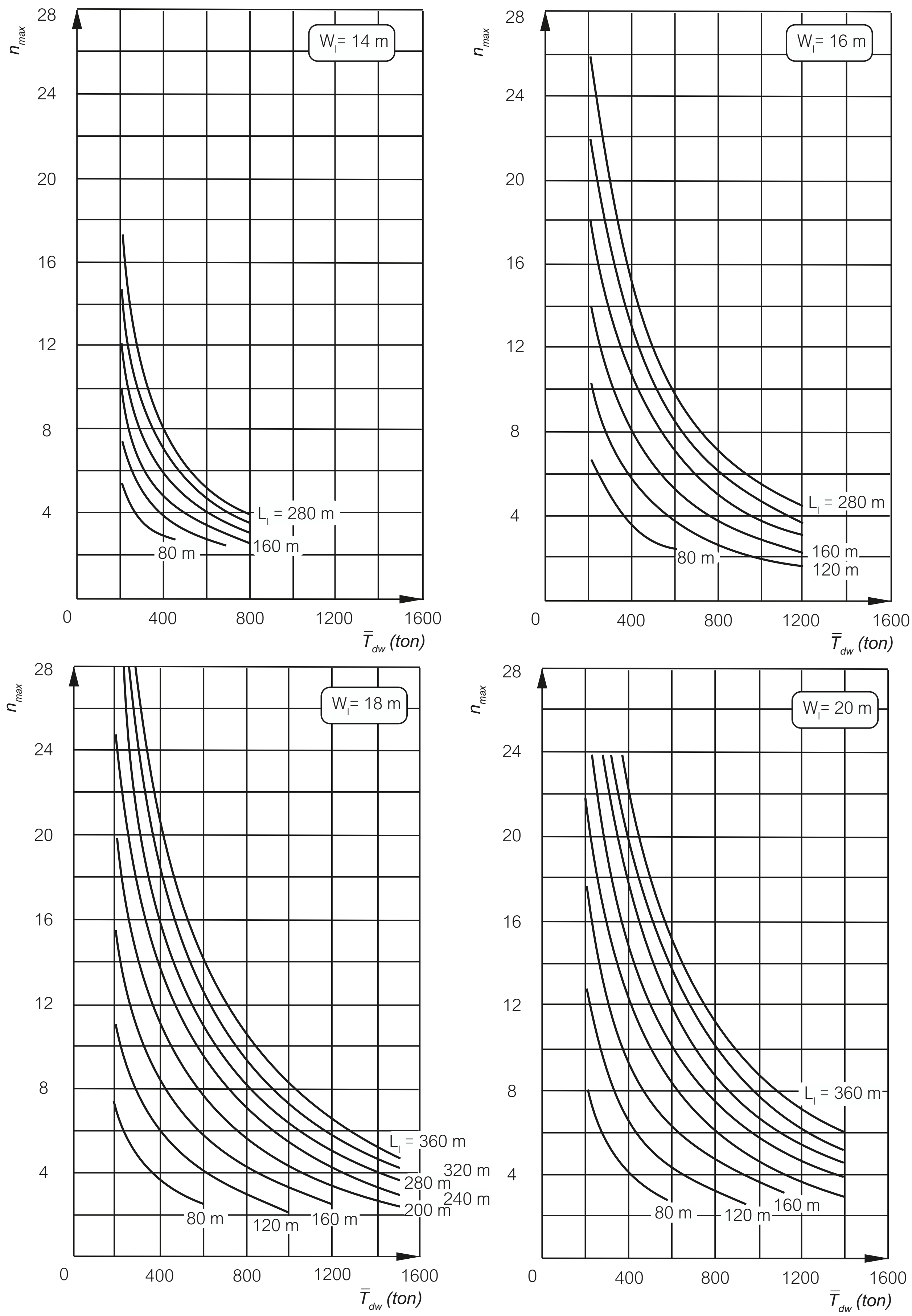


Figure 3.15: Maximum number of ships in a lock chamber, given the length and width of the chamber (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

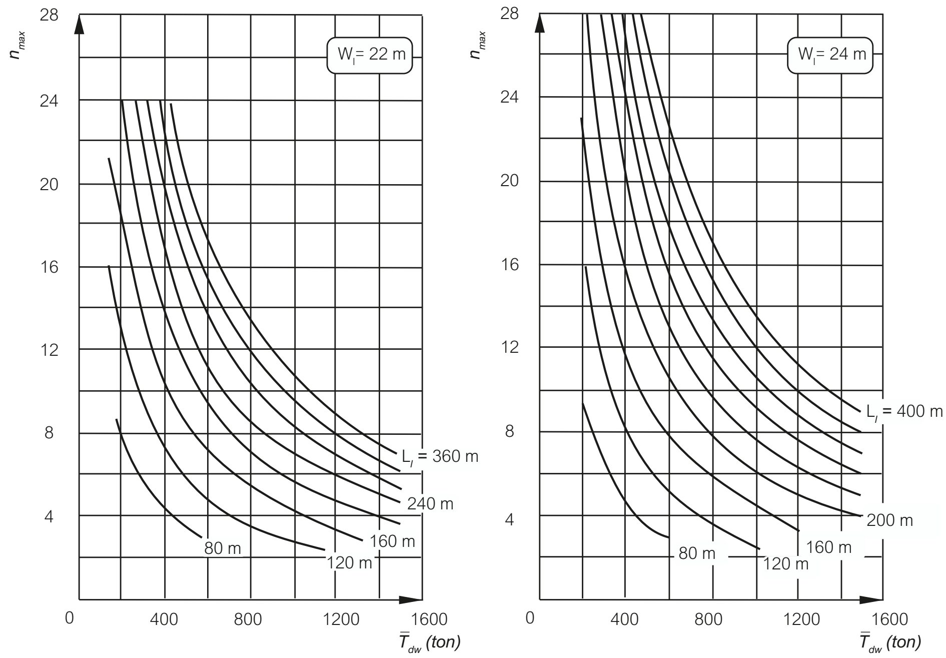


Figure 3.16: Maximum number of ships in a lock chamber, given the length and width of the chamber (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

3.1.5 Lock capacity

We will show how the locking capacity of inland waterways is calculated in three different cases:

1. always locking in two directions with fully occupied chambers;
2. always locking in one direction with fully occupied chambers and in the other direction with partially occupied chambers; and
3. always locking in one direction with fully occupied chambers (one-way traffic).

We will elaborate the first case and see what changes in the second and third case.

The fleet composition plays a role in a number of elements determining the lock capacity. Table 3.5 gives the composition used in the present example. Vessels are either fully loaded (70%) or fully unloaded (30%). The dimensions of the lock considered in this example are given in Figure 3.17.

The lock has mitre gates with sluice openings of a total of 2 m^2 in each door (so $A_{sl} = 4$ m^2) for filling and emptying the lock chamber. The energy losses are low, but not negligible. The loop distance is $S_l = 400$ m.

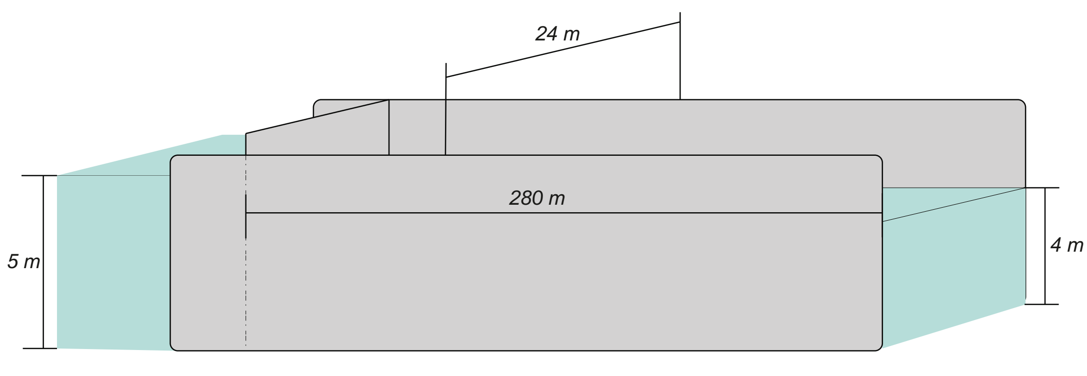


Figure 3.17: Lock dimension for lock capacity calculation (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

	P_s (%)	$T_{average}$ (tons)	$P_s \cdot T_{average}$ (tons)
	6	125	7.5
	30	325	97.5
	24	550	132.0
	22.5	925	208.1
	9	1350	121.5
	6.4	2000	128.0
	2.1	4100	86.1
Total	**100**		**780.7**

Table 3.5: Fleet data for lock capacity calculation (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Example box 3.1: Lock capacity calculations

Step 1: Maximum number of vessels in the lock chamber
Given the fleet data for T_{dw} in Table 3.5, the maximum number of vessels in the lock chamber follows from Figure 3.14, Figure 3.15 and Figure 3.16 for the relationships between the lock width, the lock length and the overall mean tonnage (780.7 tons according to Table 3.5). In this case, n_{max} = 12.

Step 2: Operating time

$$T_{op} = T_{close} + T_{waterlevel} + T_{open}$$

Table 3.1 gives: T_{close} = 2.5 min and T_{open} = 2.6 min

The time needed to adjust the water level follows from

$$T_{waterlevel} = \frac{2W_l L_{lock} H}{m A_{sl}\sqrt{2gh}}$$

With chamber width W_l = 24 m, chamber length L_{lock} = 280 m, head difference H = 1 m, discharge coefficient m = 0.8, sluice area A_{sl} = 4 m^2 and gravity acceleration g = 9.81 m/s^2 this yields approximately 14 min.

So the operating time amounts to 2.5 + 14 + 2.6 = 18.1 min.

Stap 3: Downstream entry, exit and loop times
Given the cross-sectional area of the lock chamber (A_{lock} = 5 x 24 = 120 m^2) and the average tonnage, t_i follows from Figure 3.12. For loaded vessels this is 2.4 min, for unloaded vessels 1.85 min. Since 70% is loaded, the average value is 2.24 min.

The exit time t_u follows from the same figures, but now with A_{lock} = 4 x 24 = 96 m^2. This yields an average value of 1.4 min.

The loop time $t_l = t_i + \Delta t$, where Δt follows from Figure 3.14. For S_l = 400 m this yields 2.1 min for loaded vessels and 1.8 min for unloaded ones, so 2 min on average. Hence the loop time is 2.24 + 2.00 = 4.24 min.

Stap 4: Downstream locking duration
$T_{d\text{ (down)}} = t_l + (\text{n} - 1)\, t_i + T_{\text{operation}} + n t_u$ = 4.24 + (12 – 1) 2.24 + 18.1 + 12 x 1.4 = 63.8 min

Stap 5: Upstream locking duration
Following the same steps as above yields:
t_l = 4.43 min; t_i = 2.43 min; $T_{\text{operation}}$ = 18.1 min; t_u = 1.28 min; $T_{d(up)}$ = 64.6 min

Example box 3.1 – continued on next page

Example box 3.1 – continued from previous page

Stap 6: Total cycle times
$T_c = T_{d\ (\text{up})} + T_{d\ (\text{down})} = 128.4$ min $= 2.14$ hrs

Stap 7: Lock capacity
$C_s = 2\ n_{max}/T_c = 2$ x $12/2.14 = 11.21$ ships/hr
$C_T = T_{dw}C_s = 780.7$ x $11.21 = 8751$ tons/hr

If the lock chamber is only partly occupied, the procedure is:

(a) for the direction for which the capacity is to be calculated n_{max} applies; for the opposite direction $n < n_{max}$ applies;
(b) T_d is calculated for the first direction on the basis of n_{max} and for the opposite direction on the basis of n;
(c) the capacity is determined for each direction, i.e. $C_s = n_{max}/T_c$ for the first direction and $C_s = n/T_c$ for the opposite direction.

In case of one-way traffic, the procedure changes as follows:

(a) The loop time is shorter because the first ship does not have to wait until the last ship of the previous cycle has passed the waiting area;
(b) $T_c = T_{d,\text{ in the lock direction}} + T_{\text{operation}}$;
(c) The capacity follows from $C_s = n_{max}/T_c$.

The locking capacity derived in the previous section is based on a full lock chamber in every cycle. If in the lock design phase, this capacity would be chosen equal to the average traffic intensity, but unacceptable waiting times would be the result. The variation in traffic intensity occurring in practice, combined with a limited acceptable waiting time, requires a higher locking capacity.

The variations in traffic intensity are partly systematic, partly random (see Figure 3.18). The systematic variation is a combination of daily and weekly cycles. The traffic intensity is high during the day and low during the night, high during weekdays and low in the weekends.

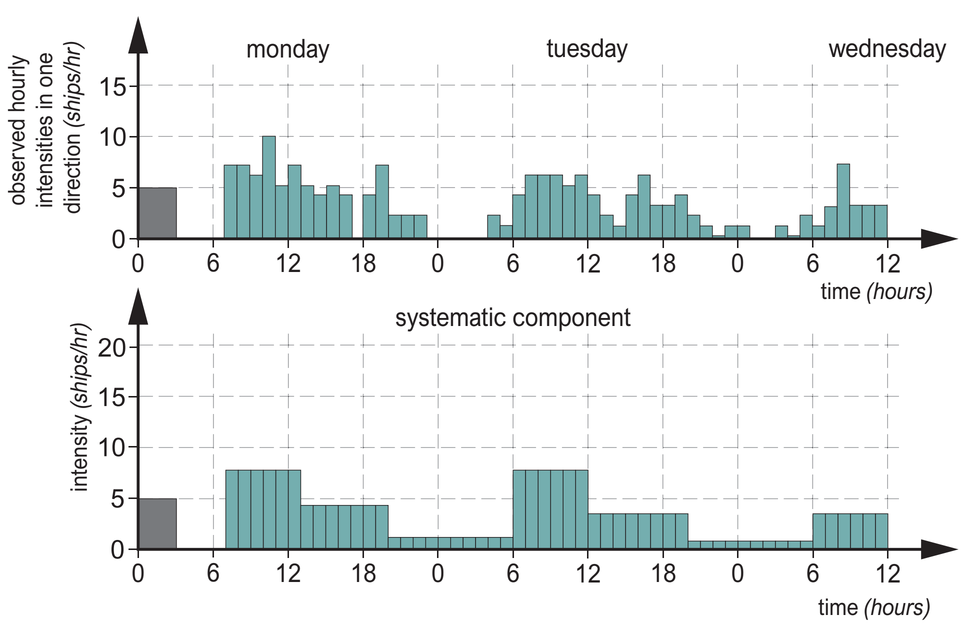


Figure 3.18: Traffic intensity variation (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Simulation models can be used to determine waiting times. Figure 3.19 qualitatively indicates how waiting times increase with the average I/C-ratio. As a result of the large intensity variations, unacceptable delays may already occur at low I/C-values. Hinder for navigation occurs if the average total waiting time exceeds 30 minutes in the busiest months. As an example: the I/C ratio at the Kreekrak locks is then about 0.55 and the intensity about 150 to 200 mln ton/year (RVW, 2020). The average passing time is about 45 to 60 minutes.

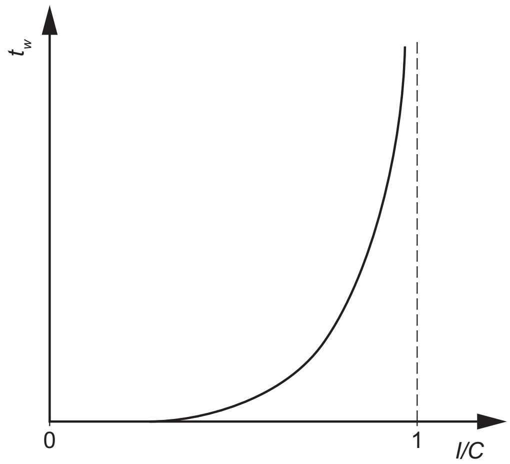


Figure 3.19: Average waiting time as a function of the average intensity/capacity ratio on a weekly basis (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

3.2 Lock dimensions

An important source of information for lock dimensions - as far as the Dutch waterways are concerned - are Rijkswaterstaat's Waterway Guidelines 2020 (RVW, 2020). In 2009 and 2019 PIANC issued design guidelines for locks and their approach areas (PIANC, 2009, 2019a), based on the national guidelines of the member states. They don't conflict with RVW (2020).

RVW (2020) gives guidelines for the dimensions of locks for commercial shipping, for recreational traffic, and for mixed traffic, including the approach and waiting areas. An important proviso is that these are guidelines, not a recipe applicable to every situation. The design of this kind of large infrastructure needs to be adapted to the local situation.

3.2.1 Locks for commercial traffic

Figure 3.20 shows the most important characteristics of the entrance and chamber parts of a lock system.

Lock chamber The actual dimensions of a lock depend on the size of the normative vessel. Table 3.6 gives the lock chamber dimensions as a function of the vessel class.

In this table, the threshold depth is defined as the draught of the normative vessel plus the required keel clearance. Since locks are designed for a life-time of typically 100 years, the possibility of lower water levels in the future due to bed erosion should also be taken into account.

The width given in this table is based on the assumption that strong guide fenders are present at the entrance of the lock chamber. If not, the lock and its entrance have to be wider.

Lock approach area RVW (2020) recommends locating the axis of the lock approach in line with the axis of the lock chamber. Furthermore, the lock approach should be straight. As indicated in Figure 3.20 it consists of four parts, which we will describe successively.

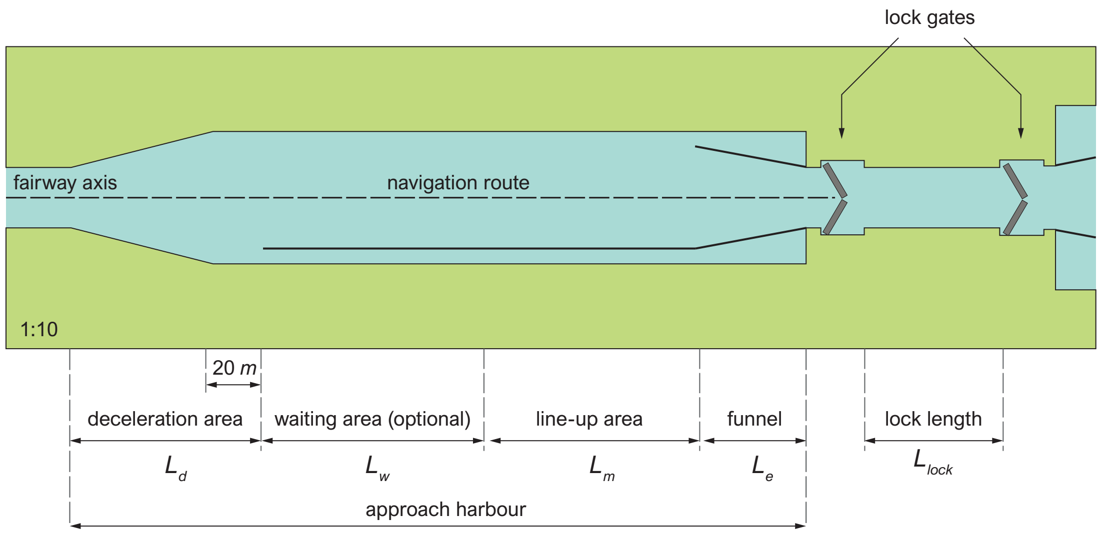


Figure 3.20: Lock approach area and chamber characteristics (image reworked from RVW, 2020, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Class CEMT	Lock length [m]	Chamber width [m]	Threshold depth [m]
I	43	6.0	2.8 – 3.1
II	60	7.5	3.1 – 3.2
III	80 – 95	9.0	3.1 – 3.3
IV	95 – 115	10.5	3.5 – 3.7
Va	125 – 150	12.5	4.2
Vb	210	12.5	4.7
VIa	160	23.8	5.0
VIb	210	23.8	5.0

Table 3.6: Lock dimensions for commercial shipping (RVW, 2020).

The length of the *deceleration area* must be sufficient to allow a vessel entering the lock approach to slow down. The length required depends on the local circumstances, the characteristics of the vessel and its initial speed. In general, it amounts to at least 2.5 times the length of the normative vessel.

The *waiting/lay-by area* is optional. It is only needed if mooring up is necessary on a regular basis, or if a separate waiting/marshalling area has to be created for ships with hazardous loads. Given that the waiting area has to be in line with the marshalling area, its width will be the same as that of the marshalling area.

The *marshalling area* must offer space to the same number of vessels as can be locked in one operation. The width of the marshalling area must therefore be equal to the width of the lock chamber. The length of this area can be taken to be 1.0 – 1.3 times the length of the lock chamber.

The *lock entrance* fulfils three functions for the ships entering the lock:

- providing visual guidance;
- providing physical support/guidance for the front part of the vessel if this is not correctly aligned with the lock axis;
- keeping vessels, when lying drifted (oblique), from becoming trapped in the lock head.

The depth of the entire lock approach must be equal to that of the connecting waterway and greater than the threshold depth, in order to prevent sedimentation problems in the approach area.

3.2.2 Locks for recreational traffic

RVW (2020) recommends using a separate (yacht) lock if there are more than 10,000 commercial passages per year on a waterway with mixed traffic. The dimensions of the yacht lock will depend on:

- the intensity of the recreational traffic;
- the dimensions of the yachts;
- the dimensions of the maintenance equipment;
- the type of recreational traffic (motor, sail or combined);
- whether it serves as a back-up for the commercial shipping lock.

Like in commercial shipping, recreational vessels are divided into classes and the dimensions of a lock are based on a normative vessel class. Due to the wide variety of types and sizes of recreational vessels, the division made is exclusively based on the yacht dimensions. For each class, these dimensions have been selected in such a way that only 5% of the vessels exceed the length, width or draught. RVW (2020) mentions different recreational classes, depending on the sailing area and type of yacht. Also European classes are given. Note that sailing yachts can have an air draught up to 30 m due to their mast. A particular category is the so-called brown fleet, a fleet of original 19th century ships, usually with brown sails; see Table 3.7.

Class	Height	Draught	Width	Length
BV1	>12.00	1.20	5.50	25.00
BV2	>12.00	1.40	6.50	30.00

Table 3.7: Normative ship dimensions - brown fleet (charter fleet) (RVW, 2020).

To determine the required lock dimensions, simulation models can be used. For commercial shipping locks, simulation models only have to be used if the traffic volume exceeds 10,000 vessels per year. For yacht locks, however, the design should always be based on simulation. Yet, some indicative dimensions can be provided:

- the threshold depth = the draught + 0.4 m;
- locks for up to 10,000 recreational vessels per year must be large enough to accommodate four vessels (two wide and two long).

3.2.3 Locks for mixed traffic

In case of mixed commercial and recreational traffic, the possibility of constructing a separate yacht lock should first be explored (see Section 3.2.2). If this is not possible (financially or spatially), a lock for mixed traffic can be considered.

Due to the small dimensions of yachts relative to commercial vessels, the size of recreational craft does not constitute a problem: recreational vessels can easily be accommodated in a lock chamber for the smallest commercial vessels (CEMT Class I). The only problem in mixed locking is the number of yachts to be accommodated in the chamber together with one or more commercial vessels. Measures are required to allow the lock to function safely. Chamber enlargement (lengthening or widening; Figure 3.21) is a good solution, yielding more space between the recreational and commercial vessels. A widened chamber has advantages over a lengthened one:

- the capacity for commercial shipping becomes significantly larger in winter times when recreational traffic is low;
- pleasure craft suffer less from turbulence caused by the propellers of the commercial vessel(s).

Yet, there are also disadvantages:

- the construction of such a lock is more expensive;
- the safety of the recreational vessels may sooner become an issue.

In view of the higher safety level, RVW (2020) recommends lengthening the lock, in which case the commercial vessels are supposed to depart slowly, thus keeping propeller-induced turbulence at a minimum.

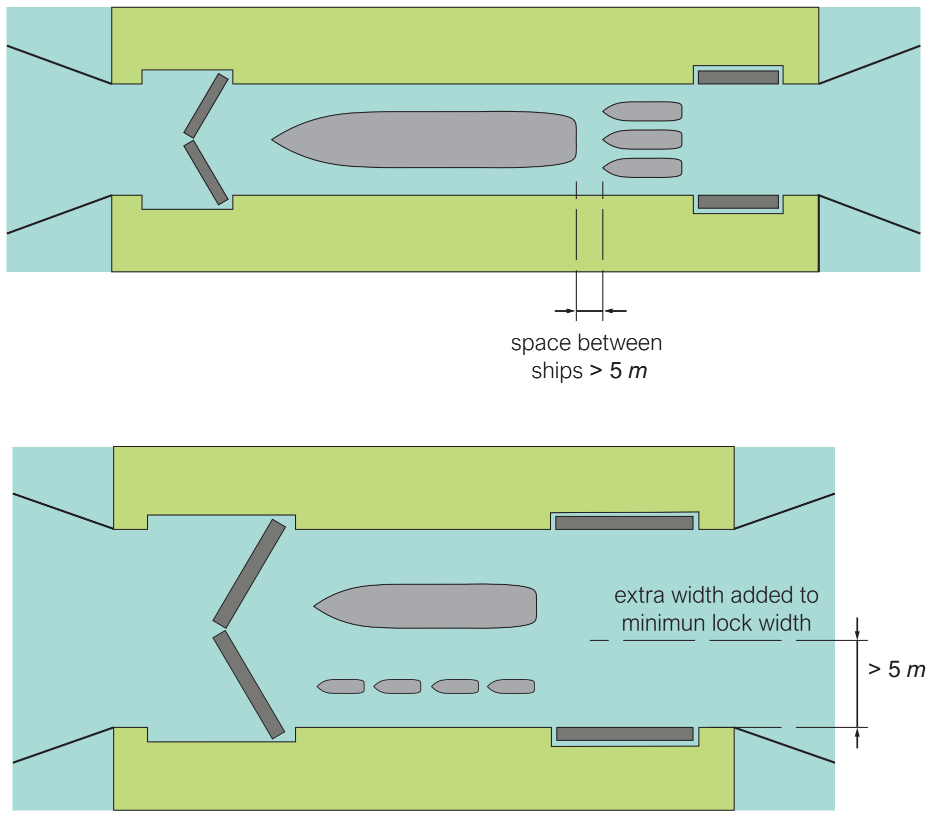


Figure 3.21: Two types of lock enlargement (image reworked from RVW, 2020, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The lock approach for mixed traffic needs several modifications:

- if there is a lot of recreational traffic, it is advisable to create a separate marshalling area (see Figure 3.22);
- in case of a single-sided marshalling area for commercial shipping, the marshalling area for recreational traffic should be on the other side and as close to the lock as possible.

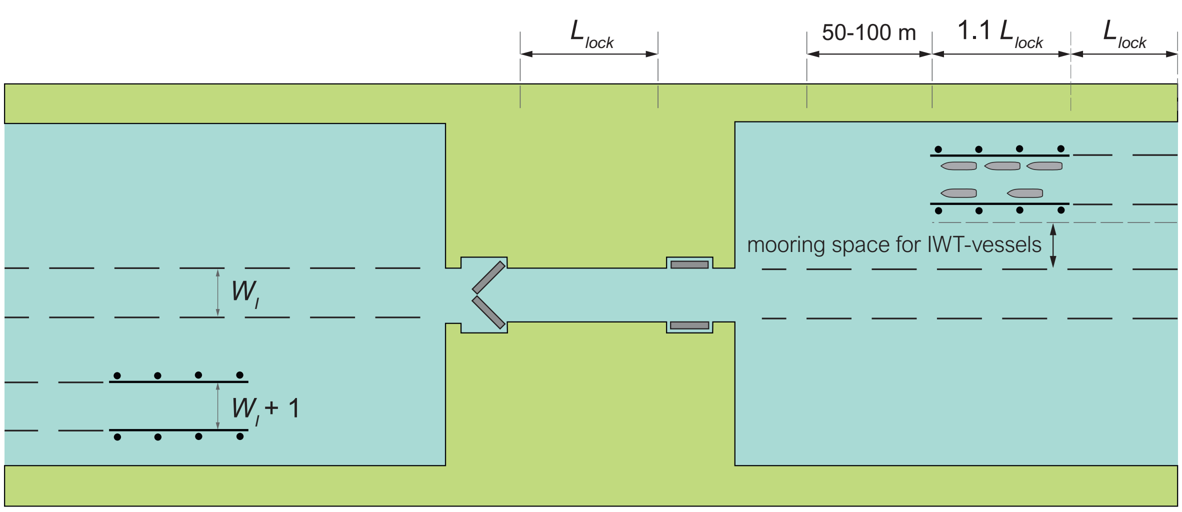


Figure 3.22: Schematic layout marshalling area with boxes for recreation traffic (image reworked from RVW, 2020, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

3.2.4 Safety lock gates

Safety lock gates (Figure 3.23, left) are part of both the waterway and the flood defence system, and must therefore meet the requirements of their flood defence function as well as those for the waterway function. When closed, the gate must function as a fully-fledged flood defence structure. For dimensions and design guidelines regarding the flood defence function in the Netherlands, we refer to Rijkswaterstaat's Helpdesk Water (https://www.helpdeskwater.nl/).

On waterways that may not be blocked, a lift lock may be installed instead of safety lock gates. A lift lock is open most of the time, except during floods. On busy waterways, safety lock gates with a lift lock alongside must always be chosen. The lift lock may be equipped with basic fittings and a 'green lock chamber' (i.e. with grass-covered slopes instead of vertical sidewalls; see Figure 3.23, right).

Figure 3.23: Left: Lift lock Kromme Nol near Heusden, Netherlands (Kromme nolkering 1 by Hullie is licenced under CC BY-SA 3.0); Right: Green lock chamber, Wilhelminasluis near Andel, Netherlands (Netherlands, Afgedamde Maas, Wilhelminasluis by Vincent van Zeijst is licenced under CC BY-SA 3.0).

The axis of the lock must coincide with that of the waterway section in which it is situated, to provide a good view of oncoming traffic and to allow vessels to pass in a straight line. This also leaves room for a waiting area.

The cross section of a lock with safety lock gates is based on a rectangular shape. If more than 15,000 commercial vessels pass per year, the lock must have the same navigable width as the waterway to ensure fully uninterrupted navigation. In less busy waterways it is the competent authority's discretion to allow a slight reduction (up to 10%) of the width. In that case, overhauling and passing in the lock are assumed to be avoidable. Where there is a single-lane profile, the minimum lock width for vessels up to Class Va is 1.6 B_s (B_s = beam of reference vessel). A width of 1.7 B_s applies to class Vb if the units are equipped with a bow thruster, and 2.0 B_s otherwise.

In case of existing waterways, the existing width is starting point for the design of the safety lock gate. For longitudinal currents > 0.5 m/s (rivers) an additional width should be applied per shipping lane. For all classes, at least 1.4 times the draught of the reference vessel is required for the sill depth and above the ground sills. Only for narrow and single-lane profiles, a factor 1.3 applies.

Where the passage is long, an increment is applied to the width. This increment varies linearly from 0 if the passage length is less than 0.3 L_s (L_s = the length of the reference vessel) to 0.02 L_s for a passage length of 0.7 L_s or more.

At safety lock gates with an adjacent lift lock, waiting areas, marshalling areas and guide fenders must be provided. If there is no lift lock, waiting areas must be provided to prevent blockage of the waterway. Where there is a normal or narrow profile, no guide fenders are required, but protective structures are required before any elements susceptible to collision. Guide fenders must be provided where there is a single-lane profile.

Apart from flood gates and lift locks that are only closed during floods, there are also 'common' locks with a flood defence function. They are located in a flood defence separating water bodies with different water levels under normal conditions, or with fresh and saline waters (see, for instance, Figure 3.24). The design of such locks is largely the same as for locks without a flood defence function, except that the doors and the plateau in the flood retaining lock head have to meet special requirements, such as height, back-up closure facilities, etc.

Figure 3.24: Navigation locks in the Afsluitdijk at Kornwerderzand ("Afsluitdijk overview prior to project start" by Royal Van Oord is licensed under CC BY-NC-SA 4.0).

3.2.5 Locks at weirs

If a navigable river is provided with a weir or navigation-blocking obstacle, traffic bypasses via a lock. The canal leading to and from the lock must branch off from the main fairway at a sufficient distance from the lock, in order to enable vessels to safely leave or enter the river's mainstream. This requires special attention upstream of the weir. There the river section between the branching point and the weir (when closed) needs to be closed off for navigation, either by prohibitory signs (for channel less than 60 m wide), or by special marking lines with yellow barrels in case of wider channels.

That this is important became evident when in December 2016, during a dense fog, a tanker hit the weir in the river Maas near Grave, Netherlands. Not only was the weir structure damaged, but also the water level in the river section upstream and all connected waters was lowered (Figure 3.25). It took months before the old situation could be restored. Based on this accident RVW (2020) provides new guidelines.

Figure 3.25: Damage to the weir at Grave (left) and the consequences upstream (right) (left: Stuw Grave aanvaring by Nico van Lammeren is licenced under CC0 1.0; right: BootAanBoot.NL, all rights reserved).

3.3 Bridges

Important aspects of bridges are their location, the way they cross the fairway, whether they are fixed or movable and the guidance and protection works. We will consider these aspects in the next sections.

3.3.1 Location

The location of a bridge is determined not only by nautical arguments, but also by factors such as the connecting infrastructure (road, railway), the environment (urban or rural) and the space available (designated or protected areas). If there is freedom of location, bridges should preferably cross the fairway perpendicularly and away from bends. If there is no other option than positioning a bridge in a bend, it has to meet specfic requirements (see RVW, 2020). In straight reaches, bridges should be located at such distances apart that safe navigation is possible, i.e. (if L_s is the length of the reference vessel):

- skippers have enough time and distance (3 L_s) to correct the vessel's course if the bridge constitutes a hindrance in the fairway;
- successive movable bridges are either so close together that they can be considered as a single long passage (in which case they need to be opened and closed in tandem), or they are sufficiently far apart to enable vessels to safely slow down and moor if necessary (total distance needed 3 L_s), and subsequently to accelerate and align with the fairway axis (total distance needed 1.5 L_s);
- skippers of vessels with an adjustable wheelhouse, such as container ships, have enough time and distance (at least 500 m) to lower the wheelhouse before passing the bridge and lift it again afterwards;
- false radar signals are avoided as much as possible.

For fixed bridges without a pier in the fairway and a passage width equal to the total fairway width there is no requirement as to the distance between them, only that before and after a bend an straight section of 1.5 L_s is required. Such bridges are preferred in general, as there is no hindrance or risk for passing vessels, like piers. In fairway reaches with strong cross-winds, the distance between consecutive bridges has to be 3 L_s. This distance also applies to bridges with a pier in the middle.

The preferred way of crossing a fairway is perpendicular but this is not always possible. In case of an oblique crossing, it is important that the axis of the passage coincides with the fairway axis. The substructure of the bridge and the guiding fenders should align with this, as indicated in Figure 3.26.

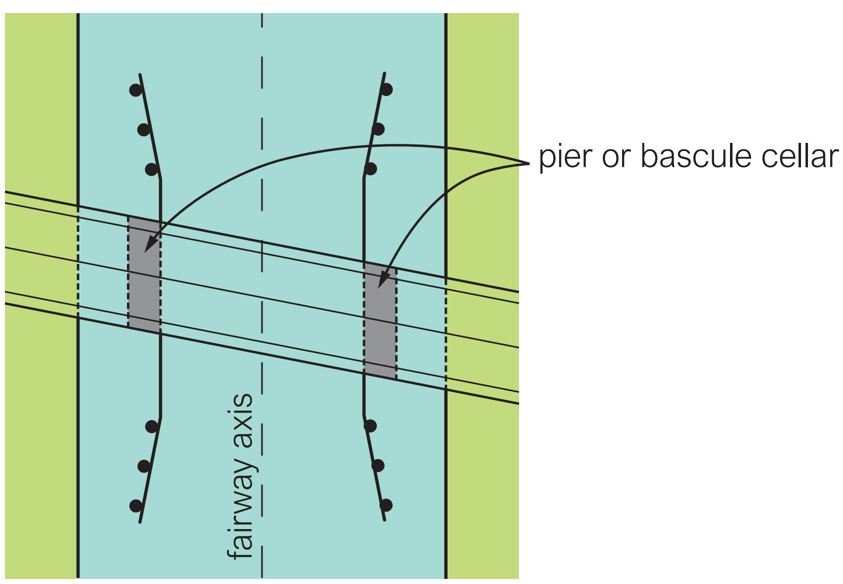


Figure 3.26: Oblique bridge crossing (reworked from RVW, 2020, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

3.3.2 Fixed or movable?

RVW (2020) distinguishes fixed and movable bridges, for commercial and recreational navigation, with a normal, narrow or single-lane fairway profile. Fixed bridges of sufficient height are preferred, because they are cheaper, require less maintenance, need no operation and don't lead to waiting times for land and waterway traffic.

Yet, there are exceptions, because some waterways have been designated as free from height limitations. Among them are maritime accesses, waterways for high transports and the so-called 'standing mast' routes for recreational vessels. Such open waterways should be crossed via movable bridges (leading to waiting times), or via tunnels or aqueducts.

At waterways with a current of more than 0.5 m/s, fixed bridges are preferable, with sufficient headroom and a free spans, so without bridge piers in the navigable part of the waterway. If bridge piers are necessary, the navigable width shall not be less than that of existing or planned bridges in the vicinity.

Fixed bridges Fixed bridges for commercial navigation have a free span over the entire fairway width. In case of new bridges, the fairway profile may not be narrowed. For existing bridges reductions are allowed, depending on the type of fairway (see Figure 3.27).

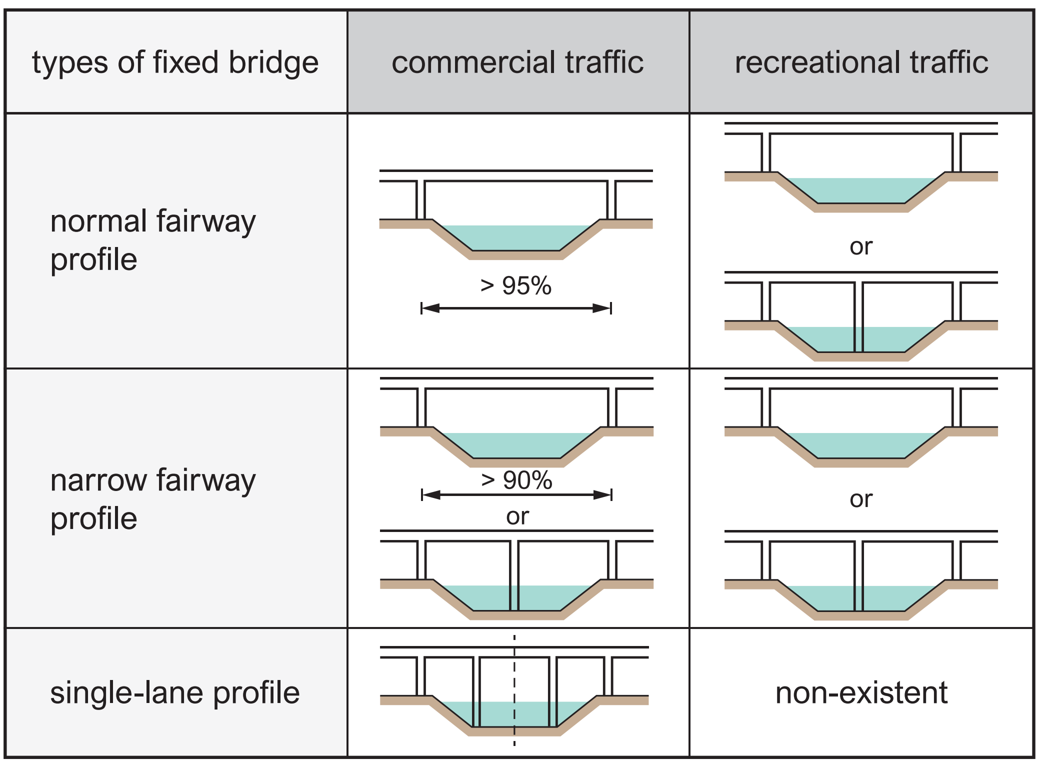
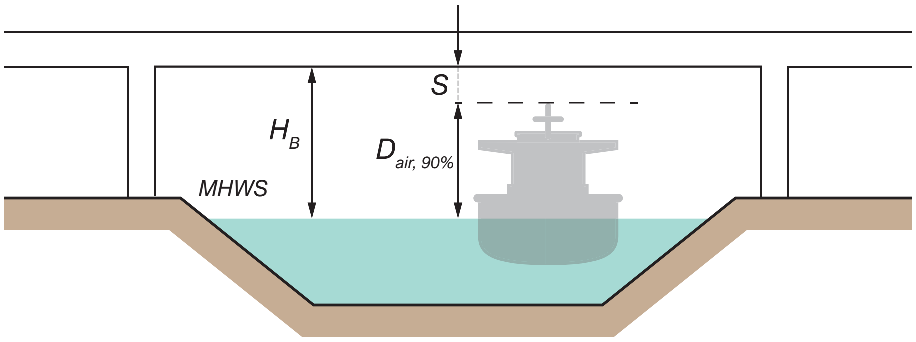


Figure 3.27: Overview of fixed bridges (reworked from RVW, 2020, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The required headroom of a fixed bridge is the same for all three fairway profiles. The reference vessel must be able to pass the bridge without hindrance. The headroom H_B is defined as the distance between the local reference high water level and the underside of the fully laden bridge. The headroom required for navigation is given by:

$$H_B = D_{\text{air, 90\%}} + S \tag{3.15}$$

in which $D_{\text{air, 90\%}}$ is the air draught or height above the waterline not exceeded by 90% of the unladen vessels in a certain CEMT class and S is a safety margin. The table in Figure 3.28 gives an overview of the headroom per CEMT-class.



class	headroom
I	5.25 m
II	6.1 m
III	6.6 m
IV	7.0 m
V	9.1 m
VIa,b,c	9.1 m

Figure 3.28: Overview of fixed bridges (reworked from RVW, 2020, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The fairway manager has to indicate the actual headroom by scales mounted on the bridge or fixed in a vertical position otherwise (see Section 5.1, Figure 5.5).

Fixed bridges over fairways used exclusively for recreational purposes have to meet different requirements. RVW (2020) differentiates the required height and width dimensions by the importance of the waterway.

For further reading, for example on the passage width in more complex situations, we refer to RVW (2020).

Movable bridges Bridges over fairways of normal width for commercial traffic always have to be fixed. Movable bridge are only allowed for narrow or single-lane fairways (see Figure 3.29).

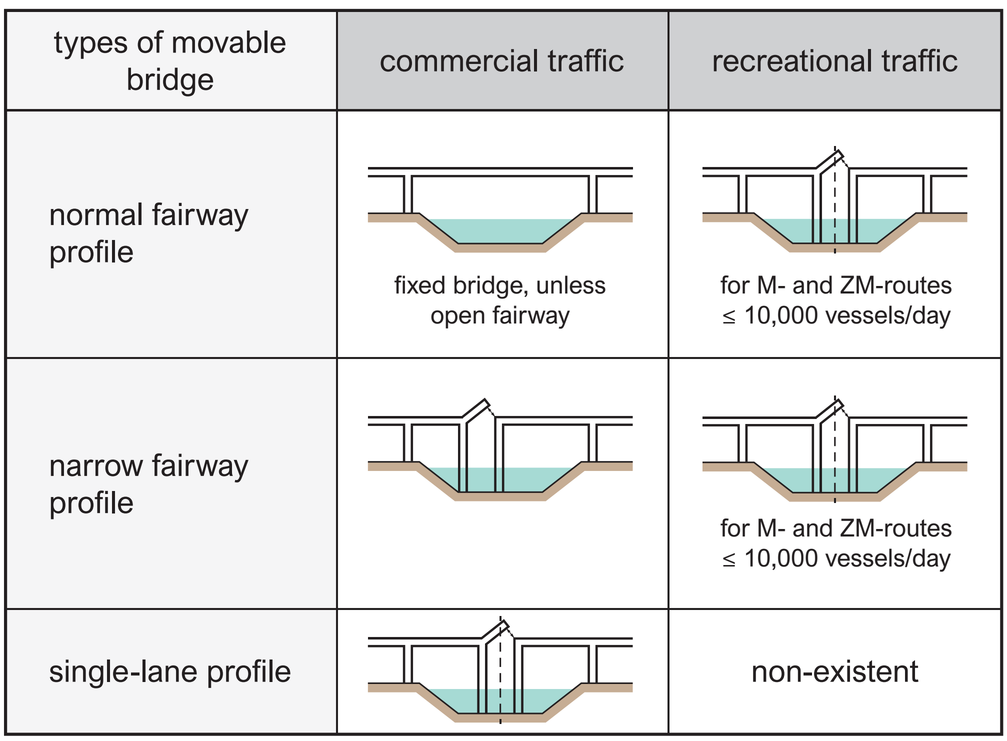


Figure 3.29: Types of movable bridges (reworked from RVW, 2020, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

In order to avoid too many openings, RVW (2020) give requirements to the headroom under a movable bridge when closed (Table 3.8). The four options mentioned in this table refer to the following situations:

- *high* – applies to the normal profile; the bridge must not hinder commercial navigation; the bridge is opened only for high transports and sailing vessels with a standing mast;
- *container* – numbers are based on containers of standard height; vessels with high cube containers have to adapt to the existing headroom;
- *medium* – applies to the narrow profile; the bridge may cause some hindrance, as it needs to be opened for about 25% of the unloaded reference vessels;
- *low* – the headroom of 1.0 m applies to the single-lane profile without recreational traffic; it means that the bridge needs to be opened for almost every passing vessel; this can be avoided by taking a headroom of 5.5 m.

vessel class	headroom option (m)			
	high	container	middle	low
I	5.25	5.25	4.75	0.5m - 1.0m or height of recreational traffic
II	6.1	5.6	5.6	
III	6.6	6.2	6.2	
IV	7.0	7.0	6.4	
V	9.1	9.1	7.4	
VIa,b,c	9.1	0.1	not appl.	not appl.

Table 3.8: Headroom under movable bridges when closed (reworked from RVW, 2020, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The passage width under the movable part of a bridge is determined by considerations of smooth and safe navigation, as well as minimal hindrance for the traffic on land and on water. Table 3.9 gives a summary. In situations with strong cross-winds, additional width may be required.

vessel class	fairway profile		
	normal	narrow	single-lane
I	fixed bridge, unless it concerns an open fairway	8.5	7.0
II		10.5	8.5
III		12.0	10.5
IV		14.0	12.0
Va		16.5	14.5
Vb		19.0	16.5
VIa,b,c		not appl.	not appl.

Table 3.9: Passage width (m) for commercial traffic under movable bridges (reworked from RVW, 2020, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

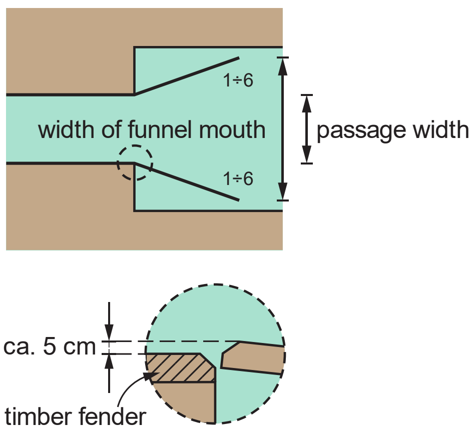
In principle, movable bridges over recreational waterways are only necessary for sailing boats. In that case, the axis of the passage must coincide with the fairway axis. The headroom for recreational traffic is not regulated, but has to be considered for the specific situation at hand (also see Table 3.8).

As movable bridges are not always open, they need to be provided with waiting areas at either side. Such a waiting area is located at the starboard side of the fairway and a vessel must be able to safely moor, unmoor and manoeuvre in front of the bridge. Furthermore, ongoing traffic may not be hindered by waiting vessels.

Finally, it should be noted that the wetted cross-section on the spot of a bridge passage should be reduced as little as possible as to prevent too strong suction phenomena. It is advised to limit the reduction of the wetted profile on the spot of a bridge to maximally 15% of the preferred waterway profile. The recommended depth of the waterway should be present over the entire width between the bridge piers.

3.3.3 Guide and protection works

Fender and guide works are meant to prevent damage to vessels and bridge. Design criteria are quite similar to those for locks. Guide works may not reduce the passage width by more than 5 cm at either side. They are required if the passage width is less than the values indicated in Figure 3.30.



fairway pro! le	vessel class I - Va		class Vb
	no bow thruster	with bow thruster	with bow thruster
single-lane	1.8 B_s	1.6 B_s	1.8 B_s
narrow	1.8 B_s	1.6 B_s	1.8 B_s
normal	2.0 B_s	1.8 B_s	2.0 B_s

Figure 3.30: Passage width requiring guide fenders, where B_s is the width of the reference vessel (reworked from RVW, 2020, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Sometimes the bridge needs a heavier protection structure. This is the case, for instance, with the City Bridge in Kampen (NL), which was estimated not to be able to withstand a collision with a rapidly moving, fully loaded large vessel. Therefore, the bridge piers are protected with concrete ramps in front (Figure 3.31).

Figure 3.31: Left: City Bridge, Kampen (NL), without concrete ramps (Kampen stadsbrug hefgedeelte by Arend041 is licenced under CC0 1.0); right: with concrete ramps (courtesy Yttje Feddes is licenced under CC BY-NC-SA 4.0).

For further reading about guide and protection works, as well as signs and signals around bridges, we refer to RVW (2020).

4 Ship-waterway and ship-ship interactions

[1]Sailing ships influence the bed and banks of navigation channels and vice versa. The same goes for the sailing behaviour of other ships. This chapter deals with these interactions.

A ship sailing with a certain speed will displace an amount of water. The ship's bow will constantly push water to the front, aside and downwards, and a corresponding amount of water returns behind the stern. This induces a so-called return current along and under the ship, against the sailing direction. The return current induces a water-level depression around the ship. This must be kept in mind when calculating the water depth under the keel or Under Keel Clearance (UKC), otherwise the ship may run aground.

Figure 4.1: Primary, secondary and propeller jet water motion (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The ship-induced water motion (see Figure 4.1) is composed of a primary and a secondary component, as well as jets from propellers and thrusters. The primary water motion is linked directly to the water displacement by the ship and consists of the return current and the accompanying water level depression. Looking at it from a fixed point, the primary motion is a (forced, long) wave, since it moves along with the ship and extends over its entire length.

The secondary water motion consists of ship-induced (free, short) waves. The height of these waves is strongly determined by the speed of the ship, but also depends on the ship's main dimensions and the hull shape. Furthermore, the secondary water motion depends on the primary one. The ship-induced waves will increase as the ship speed increases, and as the return current and the water level depression decrease. This explains why smaller and faster ships usually cause bank erosion by secondary waves; larger and slower ships by the return current.

[1]This chapter made use of '*Inland Waterways. Ports, Waterways and Inland Navigation*' (Verheij et al., 2008) and '*Capacities of Inland Waterways*' (Groenveld et al., 2006), lecture notes for the Ports and Waterways courses CIE4330 and CIE5306 at TU Delft, respectively.

The third component, the jets of bow thrusters and main propellers, may cause bed and bank erosion and exert forces on nearby structures.

In this chapter we will first discuss the primary and secondary water motion, and then the jets induced by propulsion systems. We will furthermore discuss some specific aspects of the induced water motions, and consider the net result of propulsion and resistance: the ship speed. Finally, we will show some applications of CFD models to ship-induced hydrodynamics. Most of the information provided is based on Dutch research and published in the M1115 reports of Delft Hydraulics (1988) or Rock Manual (CIRIA; CUR; CETMEF, 2007). Another important source of information is the BAW manual (BAW, 2011), which is based on research in Germany.

Within the framework of prevailing rules and regulations (see, for instance, RVW, 2020) ship-induced water motions determine the design of waterways, in particular the required bed and bank protections.

4.1 Primary water motion

The primary water motion can be explained from Bernoulli's theorem and the equation of continuity. These equations, rewritten in terms of energy conservation, were formulated and solved analytically by Schijf (1949) (also see Janssen and Schijf, 1953). Schijf also found proof for the so-called natural limit speed for ships, which we will also discuss. Bouwmeester (1977) derived the return current and the water level depression from a momentum conservation principle (which Bernoulli's theorem basically is). We will briefly discuss this alternative approach. In Germany, the derivation by Schijf is attributed to Thiele (1901) and Krey (1913).

The water motion around sailing vessels is very complicated, particularly because of the three-dimensional current pattern next to and underneath the ship and along the hull. With respect to the resistance experienced, the shape of most inland vessels is not ideal, due to their large amidships cross-section and their large block coefficient. Furthermore, the limited width and depth of inland waterways play an important role in the water motion.

As mentioned in the introduction, the return current causes a depression of the water level around the ship, causing a sinkage of the ship of approximately the same magnitude. This sinkage is mostly combined with a positive trim, due to the water level depression caused by the propeller jet.

4.1.1 Energy conservation approach

Assume the three-dimensional flow can be simplified to one-dimensional, that the ship's sinkage is equal to the water-level depression, and that the ship has no trim. In that case there is an exact analytical solution. Furthermore, we assume:

- a straight, infinitely long prismatic channel section;
- a prismatic shape of the ship (i.e. the cross-section amidships applies over the entire length);
- a constant speed of the ship;
- the course of the ship is strictly parallel to the channel axis;
- a uniform return current over the entire wet channel profile, beside as well as below the ship;
- a uniform water level depression over the entire channel width;
- no energy losses, i.e. shear stress and inertial losses are neglected;
- no influence of ship-initiated waves or phenomena caused by helical motion.

Taking a Lagrangian approach, we fix the co-ordinate system to the ship. This means that the undisturbed water is apparently flowing with velocity V_s against the ship's sailing direction (Figure 4.2). Alongside and under the ship the velocity will become equal to $(V_s + U_r)$.

Using Bernoulli's theorem between cross-sections I and II in Figure 4.2, considering the total head $H = h_0 + \frac{V_s^2}{2g}$ and $h_I - h_{II} = z$, gives:

$$z = \frac{(V_s + U_r)^2}{2g} - \frac{V_s^2}{2g} = \frac{V_s U_r}{g} + \frac{U_r^2}{2g} \tag{4.1}$$

Continuity between cross-section I and II requires (for explanation of symbols also see Figure 4.3):

$$Q = V_s A_c = (V_s + U_r)(A_c - A_s - W_s z) \tag{4.2}$$

in which:

A_c = $W_s h_0$ = wet cross-sectional area of the undisturbed channel [m^2]
A_s = $B_s D_s$ = ship's underwater cross-section amidships [m^2]
h_0 = undisturbed water depth in the channel [m]
W_s = undisturbed channel width at the water surface [m]
B_s = the ship's beam [m]
D_s = draught of the ship [m]
V_s = ship speed [m/s]
z = maximum water-level depression [m]
U_r = maximum return current velocity along the ship [m/s]

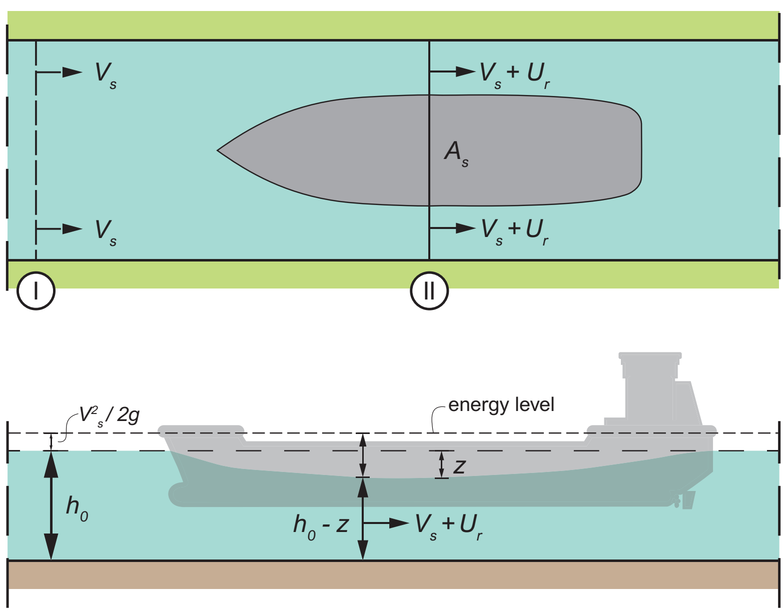


Figure 4.2: Relative water motion in a ship-fixed coordinate system (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

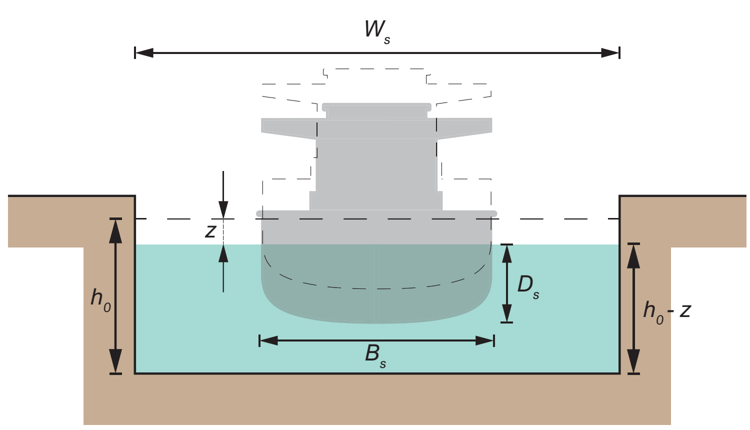


Figure 4.3: Definition of symbols at the cross-section amidships (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Limit speed

The depth and width restrictions of the waterway influence the speed of the ship. Schijf developed a method based on energy conservation to compute the natural limit speed. This speed is the maximum possible sailing speed (V_{lim}) for a certain ship in a restricted waterway of given dimensions. Schijf's approach applies to shallow water conditions.

According to Schijf, the limit speed of a ship is reached when the return current has become critical, i.e. the Froude number equals 1. When the ship's speed would further increase, the water motion next to the ship would become supercritical and the water depth would jump to a much smaller value. In that case, the continuity condition is not be satisfied any more, despite the higher current velocity. Consequently, water will accumulate in front of the bow, to the extent that a self-propelled ship is not able to overcome this. Sailing yachts and ships tugged from the banks are able to go faster, since they are not self-propelled. Schijf's method is therefore restricted to self-propelled ships.

Using Equation 4.2 to replace $V_s + U_r$ in Equation 4.1, realising that $A_c/W_s = \overline{h}$ and dividing by $\overline{h}$ we can derive the dimensionless:

$$\left(\frac{z}{\overline{h}}\right)^3 + \left(\frac{z}{\overline{h}}\right)^2 \left[\frac{Fr_{\overline{h}}^2}{2} - 2\left(1 - \frac{A_s}{A_c}\right)\right] + \frac{z}{\overline{h}}\left[\left(1 - \frac{A_s}{A_c}\right)^2 - Fr_{\overline{h}}^2\left(1 - \frac{A_s}{A_c}\right)\right] - Fr_{\overline{h}}^2\frac{A_s}{A_c}\left(1 - \frac{1}{2}\frac{A_s}{A_c}\right) = 0 \tag{4.3}$$

after some rearranging, in which $\overline{h} = A_c/W_s$ is the mean channel depth and $Fr_{\overline{h}}^2 = V_s^2/g\overline{h}$. From this equation z can be solved, and subsequently U_r from Equation 4.2.

If the ship sails at its limit speed, $V_s = V_{lim}$, and Equation 4.1 yields:

$$V_{lim} + U_r = \sqrt{V_{lim}^2 + 2gz} \tag{4.4}$$

whence, according to Equation 4.2,

$$Q = (V_{lim} + U_r)(A_c - A_s - W_s z) = \sqrt{V_{lim}^2 + 2gz}\,(A_c - A_s - W_s z) \tag{4.5}$$

This expresses Q as a function of z, so the value z_{lim} at which the maximum discharge occurs is found by setting $dQ/dz = 0$. This is the case for

$$\frac{z_{lim}}{\overline{h}} = \frac{1}{3}\left(1 - \frac{A_s}{A_c} - \frac{V_{lim}^2}{g\overline{h}}\right) \tag{4.6}$$

The corresponding maximum discharge follows from substitution of Equation 4.6 into Equation 4.5, to yield:

$$Q_{max} = \sqrt{V_{lim}^2 + \frac{2}{3}g\overline{h}\left(1 - \frac{A_s}{A_c} - \frac{V_{lim}^2}{g\overline{h}}\right)}\,A_c\left[1 - \frac{A_s}{A_c} - \frac{1}{3}\left(1 - \frac{A_s}{A_c} - \frac{V_{lim}^2}{g\overline{h}}\right)\right] \tag{4.7}$$

or, after some rearranging,

$$\frac{Q_{max}}{A_c\sqrt{g\overline{h}}} = \left[\frac{2}{3}\left(1 - \frac{A_s}{A_c} + \frac{1}{2}\frac{V_{lim}^2}{g\overline{h}}\right)\right]^{\frac{3}{2}} \tag{4.8}$$

Since $Q_{max} = V_{lim}A_c$ this means that

$$\frac{V_{lim}}{\sqrt{g\overline{h}}} = \left[\frac{2}{3}\left(1 - \frac{A_s}{A_c} + \frac{1}{2}\frac{V_{lim}^2}{g\overline{h}}\right)\right]^{\frac{3}{2}} \tag{4.9}$$

whence:

$$\left(\frac{V_{lim}}{\sqrt{g\bar{h}}}\right)^2 - 3\left(\frac{V_{lim}}{\sqrt{g\bar{h}}}\right)^{\frac{2}{3}} + 2\left(1 - \frac{A_s}{A_c}\right) = 0 \tag{4.10}$$

from which V_{lim} can be solved.

In the trivial case $A_s/A_c = 1$ (the ship fills the entire channel cross-section) the solution is as expected: $V_{lim} = 0$. In the extreme case of $A_s/A_c = 0$ the solution is $V_{lim} = \sqrt{g\bar{h}}$. So in infinitely wide, shallow water a ship's maximum speed is equal to the celerity of a shallow water wave. In most inland waterways A_s/A_c lies between 0.1 and 0.3.

Around a ship sailing at the limit speed the Froude number can be defined as

$$Fr_{lim} = \frac{V_{lim} + U_{lim}}{\sqrt{g\bar{h}\left(1 - \frac{A_s}{A_c} - \frac{z_{lim}}{\bar{h}}\right)}} \tag{4.11}$$

One may claim that this is the Froude number that becomes equal to 1 in case of the limit speed, but in practice one uses $Fr_{lim} = V_{lim}/\sqrt{g\bar{h}} = 1$. If the Froude number according to Equation 4.11 is set equal to 1, this means that

$$\frac{U_{lim}}{\sqrt{g\bar{h}}} = \sqrt{1 - \frac{A_s}{A_c} - \frac{z_{lim}}{\bar{h}}} - \frac{V_{lim}}{\sqrt{g\bar{h}}} = \sqrt{\frac{2}{3}\left(1 - \frac{A_s}{A_c}\right) + \frac{1}{3}\frac{V_{lim}^2}{g\bar{h}}} - \frac{V_{lim}}{\sqrt{g\bar{h}}} \tag{4.12}$$

in which we have used Equation 4.6.

Figure 4.4 shows $V_{lim}/\sqrt{g\bar{h}}$ (Equation 4.10), $z_{lim}/\bar{h}$ (Equation 4.6) and $U_{lim}/\sqrt{g\bar{h}}$ (Equation 4.12) as functions of A_s/A_c. Apart from the limit speed associated with the return current and the water level depression, there is another limit speed associated with the secondary water motion. In the next section we will derive an expression for it.

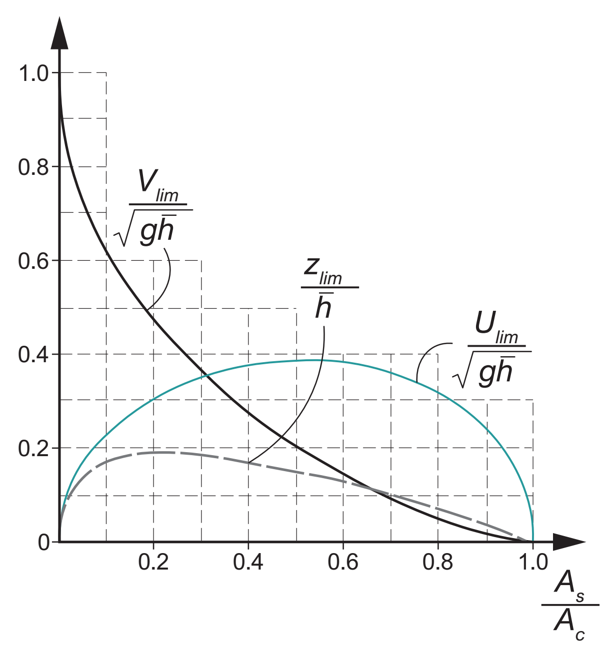


Figure 4.4: Limit values according to Schijf's theory (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

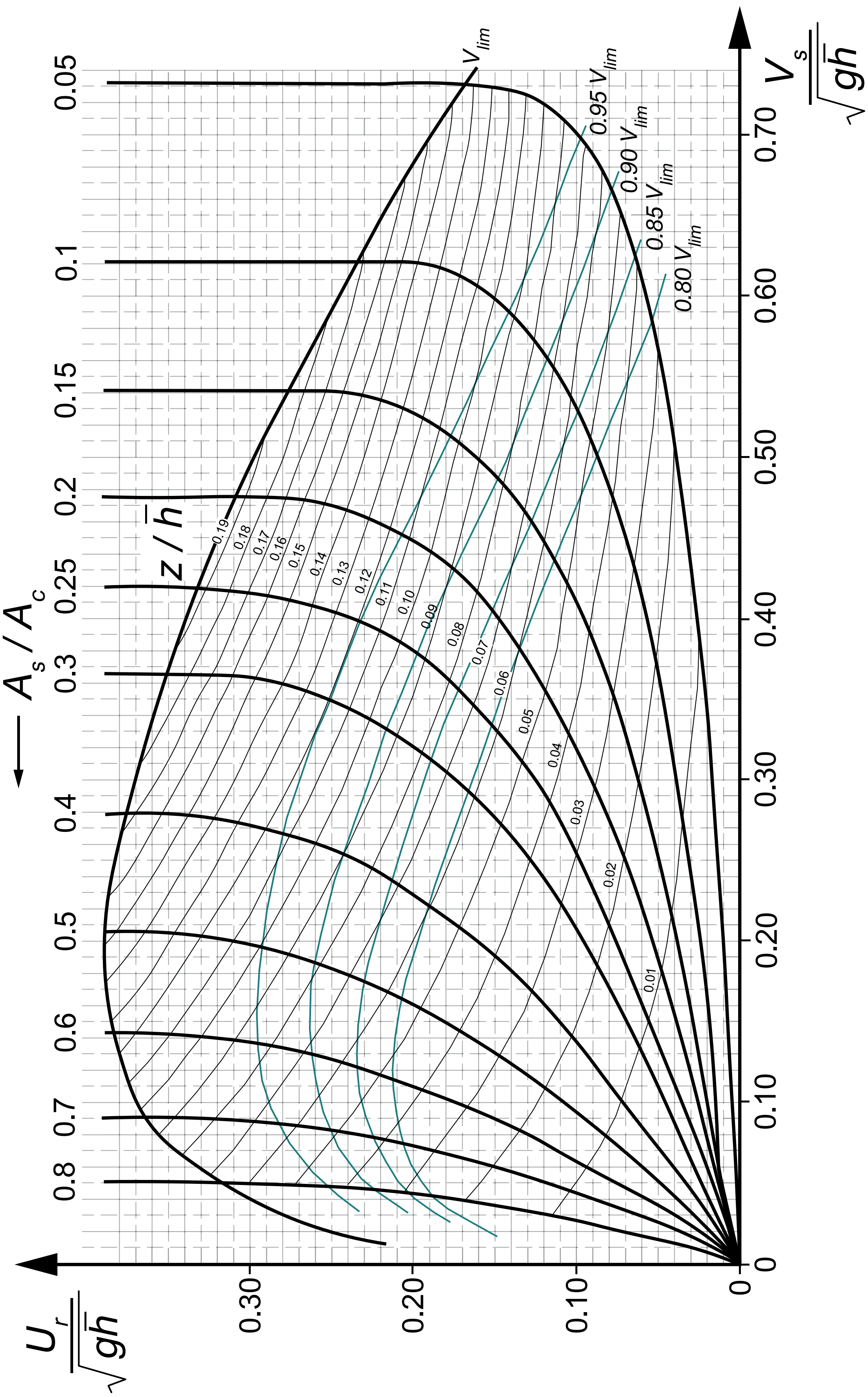


Figure 4.5: Schijf's diagram ($\alpha_{Schijf} = 1.0$) (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

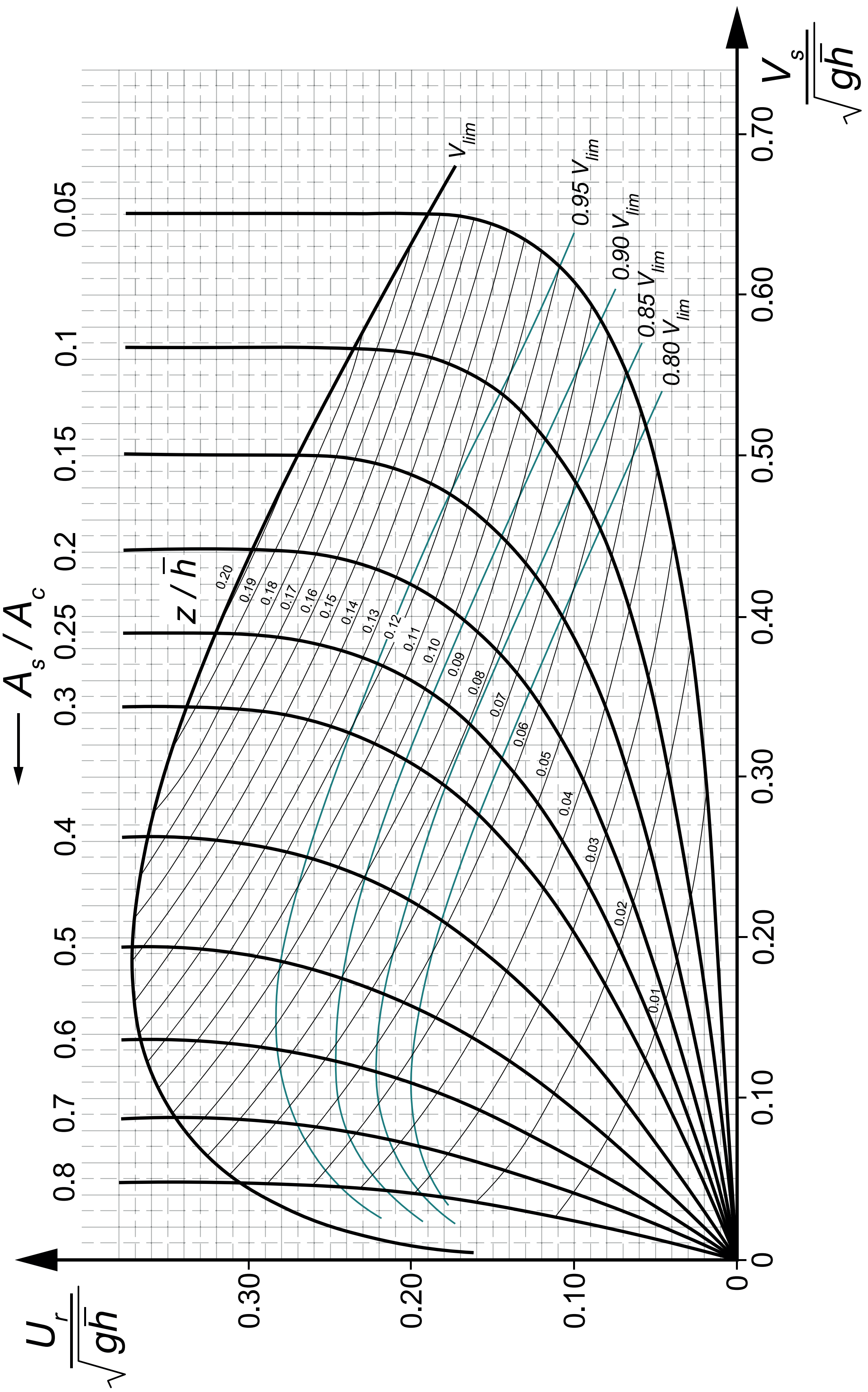


Figure 4.6: Schijf's diagram ($\alpha_{Schijf} = 1.1$) (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Correction factor

Tests (Delft Hydraulics, 1953) showed some deviations from this theory, probably due to the simplifying assumptions made. Therefore, a correction factor was introduced into Equation 4.1:

$$z = \alpha_{schijf} \frac{(V_s + U_r)^2}{2g} - \frac{V_s^2}{2g} \tag{4.13}$$

in which

$$\alpha_{schijf} = 1.4 - 0.4 \frac{V_s}{V_{lim}} \tag{4.14}$$

The correction factor generally varies between 1.05 and 1.2. A commonly used value is 1.1, which corresponds with $V_s = 0.75V_{lim}$. The effect of this correction is that the water level depression and the return current are larger than according to the original theory.

This factor is claimed to correct for the non-uniformity of the velocity field, but a comment is in order, because from a physical point of view it is not a very logical approach. Firstly, it is only applied in the expression for the energy head near the ship, not in the energy head away from the ship or in equation of continuity. Yet, applying the correction factor seems to improve the results, so it is usually maintained.

Taking this correction factor into account, the relationship between V_s, U_r and z following from Equation 4.13 and Equation 4.2 reads (Equation 4.16 follows from Equation 4.2 in a similar manner as before):

$$\frac{V_s}{\sqrt{g\overline{h}}} = \left(\frac{2\frac{z}{\overline{h}}}{\alpha_{schijf} \left(1 - \frac{A_s}{A_c} - \frac{z}{\overline{h}}\right)^{-2} - 1} \right)^{1/2} \tag{4.15}$$

$$\frac{U_r}{\sqrt{g\overline{h}}} = \frac{V_s}{\sqrt{g\overline{h}}} \left(\frac{1}{1 - \frac{A_s}{A_c} - \frac{z}{\overline{h}}} - 1 \right) \tag{4.16}$$

Figure 4.5 and Figure 4.6 show diagrams of $U_r/\sqrt{g\overline{h}}$ as a function of $V_s/\sqrt{g\overline{h}}$ for different values of $z/\overline{h}$, with $\alpha_{Schijf} = 1.0$ and 1.1, respectively. Moreover, the diagrams indicate what fraction of the limit speed each point concern. Given A_s/A_c, g, $\overline{h}$ and V_s, one can determine U_r, z and V_{lim}.

Example box 4.1: Compute V_{lim}, z_{lim}, U_{lim} and U_r

Consider a rectangular channel similar to the Amsterdam-Rhine Canal: $h_0 = \overline{h} = 5$ m and $W_s = 100$ m. The largest push-tow convoy allowed to sail in the canal, a four-barge unit, has dimensions: $L_s = 191$ m, $B_s = 22.8$ m, $D_s = 3.3$ m. The ship sails in the centreline of the canal. What are the limit conditions V_{lim}, z_{lim} and U_{lim} and what are U_r and z if $V_s = 3.5$ m/s?

The blockage coefficient A_s/A_c is a parameter that appears throughout the equations of Schijf's theory. In this case it amounts to:

$A_s/A_c = B_sD_s/W_sh_0 = 22.8 * 3.3/(100 * 5) = 0.15$

The limit speed V_{lim} can be determined in different ways:
(a) iteratively from Equation 4.10, which is the most accurate approach:

$$\left(\frac{V_{lim}}{\sqrt{g\overline{h}}}\right)^2 - 3\left(\frac{V_{lim}}{\sqrt{g\overline{h}}}\right)^{\frac{2}{3}} = -2\left(1 - \frac{A_s}{A_c}\right) = -1.70$$

Example box 4.1 – continued on next page

Example box 4.1 – continued from previous page

(b) if A_s/A_c lies between 0.1 and 0.3, Equation 4.10 can be approximated by

$$\frac{V_{lim}}{\sqrt{g\overline{h}}} \approx 0.78\left(1 - \frac{A_s}{A_c}\right)^{2.25} = 0.54$$

(c) by reading from Figure 4.5 (assuming $\alpha_{Schijf} = 1.0$), yielding $V_{lim}/\sqrt{g\overline{h}} = 0.55$.

The consensus result is $V_{lim} = 3.79$ m/s.

The limit water level depression z_{lim} preferably follows from Equation 4.6:

$$z_{lim}/\overline{h} = 1/3(1 - 0.15 - 0.541^2) = 0.186$$

yielding $z_{lim} = 0.93$ m. Reading from Figure 4.5 gives a (less accurate) value of 0.9 m.

The limit return current velocity U_{lim} follows from Equation 4.12:

$$U_{lim}/\sqrt{g\overline{h}} = \sqrt{\tfrac{2}{3}(1-0.15) + \tfrac{1}{3}0.541^2} - 0.541 = 0.274$$

so $U_{lim} = 1.91$ m/s. Reading from Figure 4.5 yields 1.89 m/s, but is less accurate.

The return current U_r when the convoy sails at 3.5 m/s can be found in two ways:

(a) iteratively from

$$((V_s + U_r)^2 - V_s^2)/(2g\overline{h}) - U_r/(V_s + U_r) + A_s/A_c = 0$$

which follows from elimination of z from Equation 4.1 and Equation 4.2. This yields $U_r = 1.13$ m/s.

(b) by reading from Figure 4.5, yielding the (less accurate) value of 1.13 m/s.

The water level depression z follows either from Equation 4.13, yielding 0.47 m, or from Figure 4.5, yielding the same result.

Non-rectangular cross-sections

Schijf's model was originally developed for rectangular channels. A simple schematisation suffices to extend the method to trapezoidal channels and actually to any shape of of cross-section, as long as it can be approximated

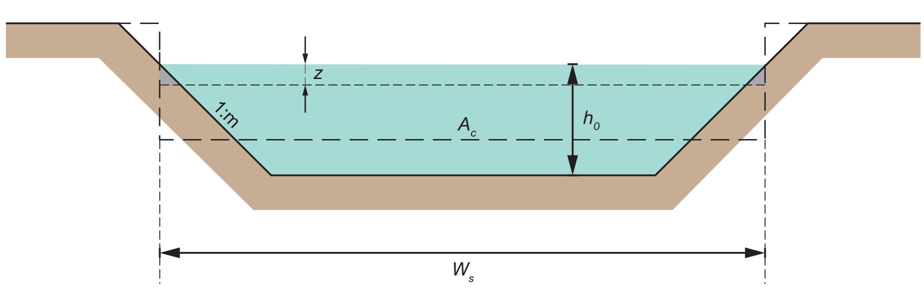


Figure 4.7: Schematisation of a trapezoidal cross-section (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

by a rectangle with the same wet cross-section and the same width at the water surface. Figure 4.7 shows this schematisation for a trapezoidal channel.

Schijf's method can be applied without modification to the schematised channel. The error due to this schematisation depends on the bank slope $(1 : m)$, the width at the water surface (W_s) and the water level depression (z). When a ship passes, there is a small error in the cross-sectional area (the grey areas in Figure 4.7), amounting to mz^2 relative to $A_c - A_s - W_s z$.

If the blockage coefficient A_s/A_c is less than 0.1, the error due to the schematisation is less than 1 to 2%. For larger blockage coefficients this may increase to some 5%.

Balanin and Bykov (1965) present equations for the limit speed in a trapezoidal canal (Equation 4.17), as well as an iterative method to determine return current and water level depression (Equation 4.18 to Equation 4.20):

$$\frac{V_{lim}}{\sqrt{gh_0}} = \sqrt{8}\left(1 - 0.325\frac{mh_0}{W_s}\right)\left[\cos\left(\frac{\pi + \arccos\left(1 - \frac{A_s}{A_c}\right)}{3}\right)\right]^{\frac{3}{2}} \tag{4.17}$$

$$z = \frac{V_s^2}{g}\left(\frac{\frac{A_c}{A_s} - 0.5}{\left(\frac{A_c}{A_s} - 1\right)^2}\right) \tag{4.18}$$

$$U_r = V_s\left(\frac{1 + z\frac{W_s}{A_s}}{\frac{A_c}{A_s} - 1 - z\frac{W_s}{A_s}}\right) \tag{4.19}$$

$$z = \frac{1}{g}(V_s + 0.5U_r)U_r \tag{4.20}$$

In a few iterations this method already yields reliable results.

In wide channels the blockage factor is small and the return current velocity is much smaller than the ship's speed. Bolt (2003) derived for the return current in that case:

$$U_r = V_s\left(\frac{\frac{A_s}{A_c}}{1 - \frac{A_s}{A_c} - Fr_h^2}\right) \tag{4.21}$$

in which Fr_h is again the Froude number related to the ship speed and the water depth.

Natural waterways with a current

The computations for channels with a current are analogous to the ones for channels without currents. Only now the velocities have to be considered relative to the current velocity in the undisturbed channel.

Suppose:

- U_c = undisturbed absolute current velocity (i.e. relative to the banks),
- V_s = absolute speed of the ship,
- V_s' = ship's speed relative to the undisturbed channel flow,
- U_r = absolute return current velocity,
- U_r' = return current velocity relative to the undisturbed channel flow.

Furthermore, we define in Figure 4.8 the direction from left to right as positive. Then the relative ship's speed to be used in the analysis is

$$V_s' = V_s - U_c \tag{4.22}$$

The method then yields the relative return current velocity U_r', after which the absolute one follows from

$$U_r = U_r' - U_c \tag{4.23}$$

The easiest way of taking the current into account is therefore to work from a ship-fixed co-ordinate system. On board of the ship one sees the undisturbed water approach at a speed V_s' and next to the ship the flow has a speed $V_s + U_r + / - U_c$. Note that U_c can be positive or negative, which means that U_r may become negative. In that case, Schijf's method does not apply.

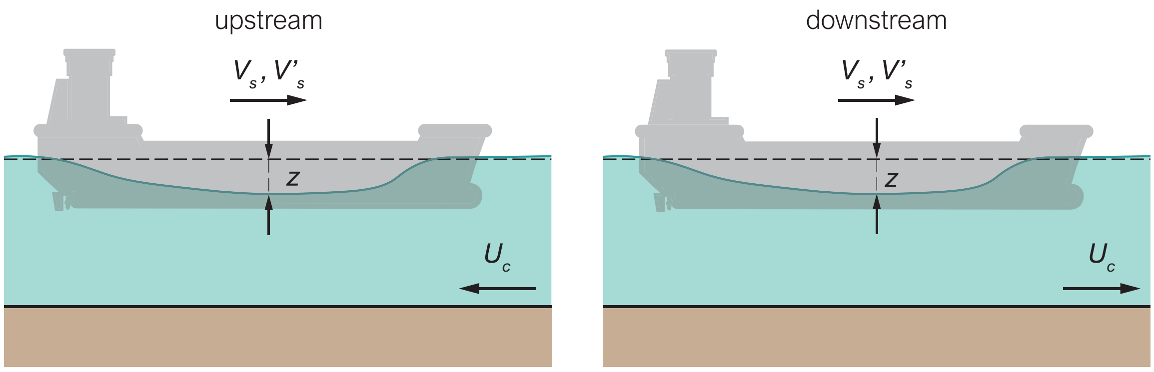


Figure 4.8: Waterway with a current (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

4.1.2 Momentum conservation approach

Instead of considering the conservation of energy of the water motion, Bouwmeester et al. (1977) considered the momentum balance for the body of water before and around the ship (the grey area in Figure 4.9). The basis of this approach is Newton's law, i.e.

$$\sum F = M \frac{dV}{dt} \tag{4.24}$$

where $\sum F$ is the sum of longitudinal forces on the water body around ship, M is the water mass considered, V is the velocity and t is time. Note that the time-derivative is a material derivative, i.e. moving along with the flow.

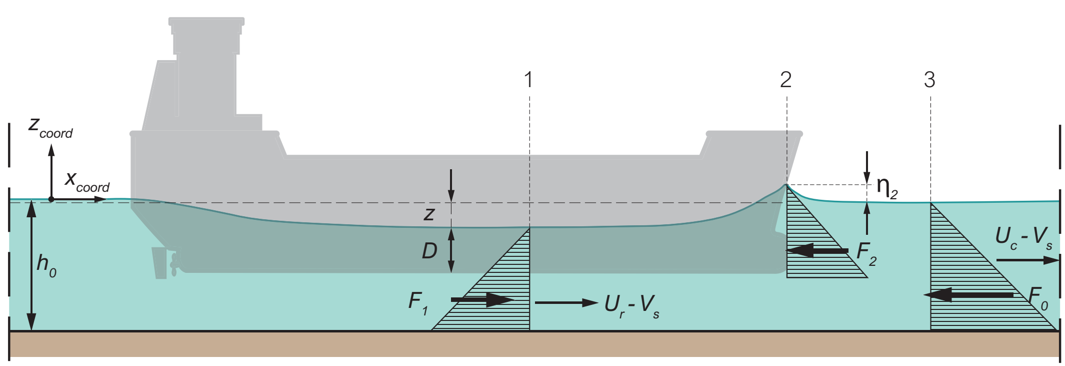


Figure 4.9: Control area of the momentum conservation approach (modified from Bouwmeester et al., 1977, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

In the case of steady horizontal frictionless water flow, this can be elaborated to

$$\frac{F_h}{\rho_w} + \frac{Q^2}{A} = \text{constant in the flow direction} \tag{4.25}$$

in which F_h is the hydrostatic force, ρ_w is the mass density of water, Q is the discharge and A is the cross-sectional area of the flow.

Because the basic conservation equations can be written in terms of energy conservation as well as momentum conservation, the results of these two approaches should be the same. Bouwmeester et al. (1977) derived their results for a trapezoidal channel, but even if they are translated to a rectangular channel, there are discrepancies, probably due to a difference in assumptions.

Sharp and Fenton (1968) developed a simplified model based on momentum conservation, assuming a rectangular cross-section ($m = 0$) and neglecting the current velocity ($U_c = 0$) and the headwater in front of the bow.

Computed values with Schijf's and Bouwmeester's approaches have been compared with measured data. In the case presented in Figure 4.10 both theories show a considerable degree of agreement in other cases larger discrepancies are found.

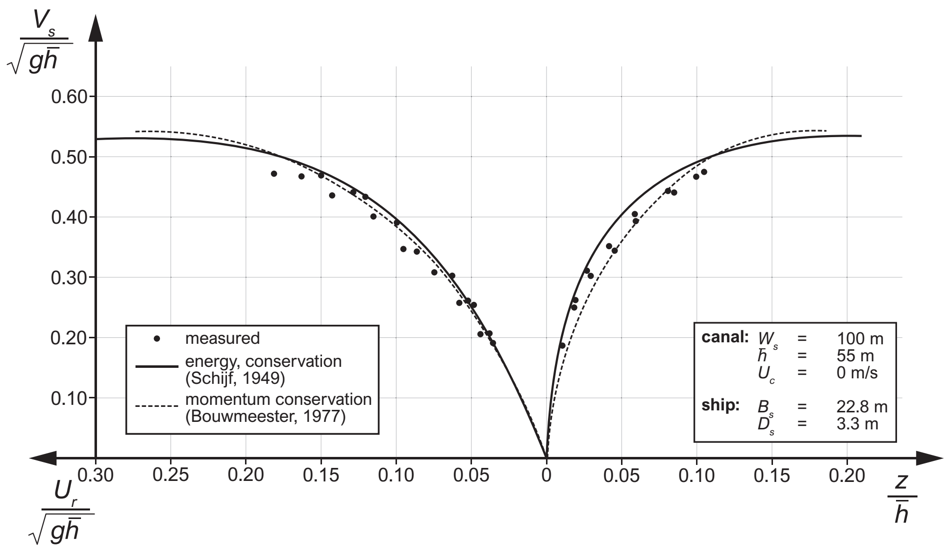


Figure 4.10: Comparison of computed and measured values for a push-tow unit (reworked from Bouwmeester et al., 1977, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

For the one-dimensional approach to be applicable, the channel width must not be much larger than the length of the ship (L_s), otherwise the assumption of uniformity across the channel will no longer hold. The ratio W_s/L_s must certainly not be larger than 1.5. Considering the fact that for inland ships the length-beam ration is usually in the order of 8, the field of application for the one-dimensional model is $2 < W_s/B_s < 12$.

Experiments (Delft Hydraulics, 1985) showed that within these constraints Bouwmeester's momentum approach gives the best results for the water level depression and the return current velocity. For conventional ships the energy method of Schijf appeared to perform within the range $2 < W_s/B_s < 4.5$. The energy method also appeared to apply well for push-barge units in the same range.

In fact the application of one-dimensional models is only permitted for ships sailing in the centre line the canal (midway). Tests in the Hartel Canal (near Rotterdam) on the water motion caused by a pushed convoy revealed that the water level depression and the return current increase as the ship sails more eccentrically (Delft Hydraulics, 1984). For the governing equations we refer to Delft Hydraulics (1988) or the (CIRIA; CUR; CETMEF, 2007).

Note, furthermore, that in the considerations so far the influence of bed, bank and hull friction has not been taken into account, since it was assumed to be of minor importance. Including these friction effects turned out to yield only 3% extra water level depression. This only applies in case of a substantial under keel clearance, otherwise the boundary layers along the ship's hull and at the canal bed will interfere.

4.2 Secondary water motion

Besides the primary wave system, sailing ships generate so-called secondary waves (though these are probably the most visible ones). At a normal sailing speed these waves remain short with respect to the ship's length. Below a relative speed of 0.233 m/s they tend to be suppressed by the surface tension. As the speed increases beyond this value, first small capillary waves (wave length < 1.7 cm) will be generated, but at still higher speeds longer gravity waves will form. These are important for navigation, but also for safety, e.g. of moored other vessels, or of people at the banks.

The theoretical basis explaining ship-induced waves was laid by Lord Kelvin (Kelvin, 1886, 1887, 1904). In his theory, he first considered a ship sailing at a constant speed as an isolated pressure point, moving over the surface of deep water while transmitting a wave pattern. Observations and theoretical investigations show that for a moving ship two groups of waves are created: one near the bow and the other in the stern region of the ship. Moreover, each of these groups consists of two systems of waves, the so-called divergent and transversal waves. The former diverge away from the axis of navigation, the latter propagate in the direction of navigation, but at a speed that decreases with the distance to the axis (Figure 4.11).

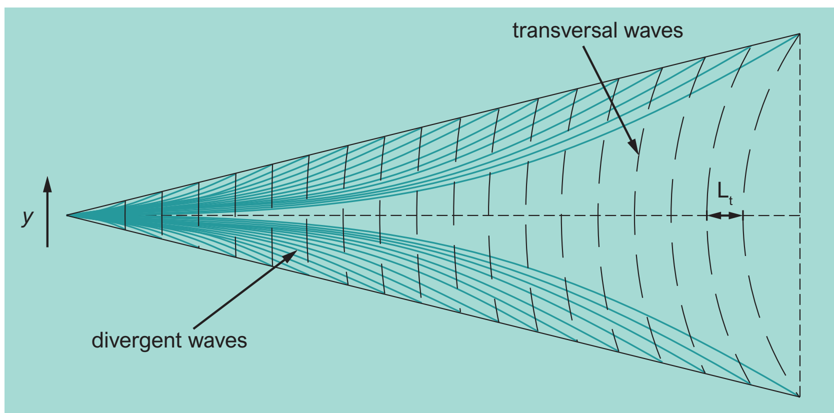


Figure 4.11: Waves according to Kelvin's moving pressure point theory (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

At the locations where the divergent and the transversal waves meet, so-called interference cusps are formed. Cusps occur at points where two or more waves arrive simultaneously. The height of the cusp is determined by the sum of the heights of the individual incoming waves. At deep water and for an isolated pressure point these cusps are located on a line at an angle of 19°28' (sin 19°28' = 1/3) with respect to the sailing line (Figure 4.12).

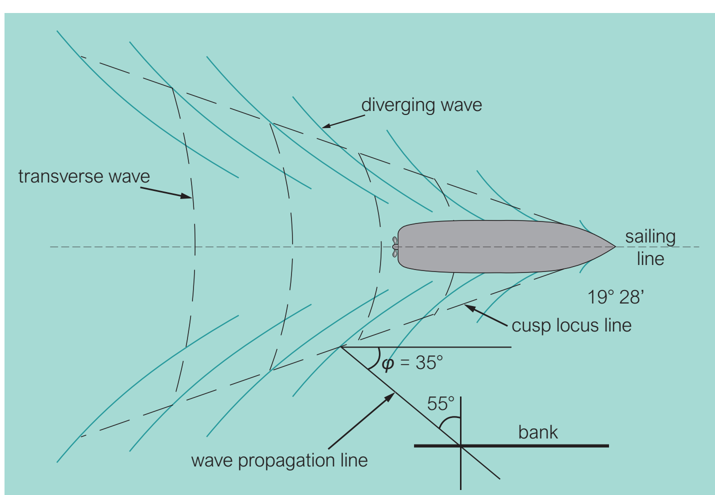


Figure 4.12: Locus of interference cusps (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Deep water A ship sailing on deep water can be seen as an assembly of a large amount of pressure points: mainly at the bow and at the stern, but also with interruptions along the water line, for example at the location between two inland barges. This causes a wave pattern around a sailing ship as shown in Figure 4.12 (only the bow system is shown).

Two systems of interference cusps are induced, viz. one at the bow and one at the stern of the ship. From observations the angle θ between the cusp lines and the sailing line appears to be a little smaller than the aforementioned 19°28', and varies between 10° and 19°28', depending on the shape of the ship. The transversal waves are usually only clearly noticeable behind the ship, since no disturbances occur outside the cusp lines from the bow.

In the navigation axis the position of the transversal wave crests with respect to the bow is given by

$$x_n = n\frac{2\pi}{g}V_p^2 = nL_t \tag{4.26}$$

where:

n	= 1, 2, 3, ... = the number of the n-th wave crest from the bow,
V_p	= the (absolute) celerity of the wave crest,
L_t	= the distance between two successive wave crests (so the wave length).

The relation between the length of the ship-induced transversal waves and the navigation speed can be determined through linear wave theory. According to this theory, for gravity waves at deep water the wave length λ and the wave celerity c are related via the dispersion relationship:

$$c^2 = \frac{g}{2\pi}\lambda \tag{4.27}$$

The sailing speed can be considered as the celerity of a certain point that induces waves. If we assume $V_p = V_s$, Equation 4.27 implies

$$L_t = \frac{2\pi}{g}V_s^2 \tag{4.28}$$

This equation reveals another natural limit velocity. If a small ship with large engine power increases its speed more and more, the wave length of the transversal wave will approach the ship's length L_s. In that case bow wave and stern wave interfere and reinforce each other to maximum amplitude. If the ship would further increase its speed, it ship would have to sail against its own bow wave, which at the same time becomes higher. As a consequence, applying more engine power does not further increase the ship's speed. Only ships with a special design can overcome this by skimming over the water. For a normal ship the limit speed follows from:

$$V_{lim} = \sqrt{\frac{g}{2\pi}L_s} \tag{4.29}$$

Shallow water From a wave perspective, waves 'feel' the bed in shallow water, which is the case if $h_0/\lambda < 0.5$. The celerity of the individual waves is now described with the dispersion relationship

$$c^2 = gk\tanh(kh_0) \tag{4.30}$$

In case of the limit speed as defined above, the corresponding shallow-water wave length is equal to the ship length, again. If we assume the wave celerity to be equal to the ship speed, we have:

$$\frac{V_{lim,\ \mathrm{shallow}}}{V_{lim,\ \mathrm{deep}}} = \sqrt{\tanh\left(\frac{2\pi h_0}{L_s}\right)} = \sqrt{\tanh\left(\frac{gh_0}{V_{lim,\ \mathrm{deep}}^2}\right)} \tag{4.31}$$

The Froude-number criterion can be used to distinguish between deep and shallow water conditions for the ship: if $Fr_h = V_s/\sqrt{gh_0} < 0.74$, the ship experiences deep water conditions.

The angle θ also depends on this ship-based Froude number. For Fr_h-values up to 0.74, the angle differs little from the 19°28' for deep water. For values larger than 0.74 a rapid increase of the angle occurs, up to 90°when the critical velocity is reached ($Fr_h = 1$), Figure 4.13. At that moment the transversal and divergent waves will coincide and create a kind of shock wave, similar to the sound barrier for flying objects at Mach 1. When the ship's speed increases further, the transversal waves disappear and only divergent waves remain. At a still higher speed, the angle θ will gradually decrease back to 19°28'. This situation, however, is not relevant for water-displacing ships, only for planing vessels such as fast ferries, see Section 4.2.4.

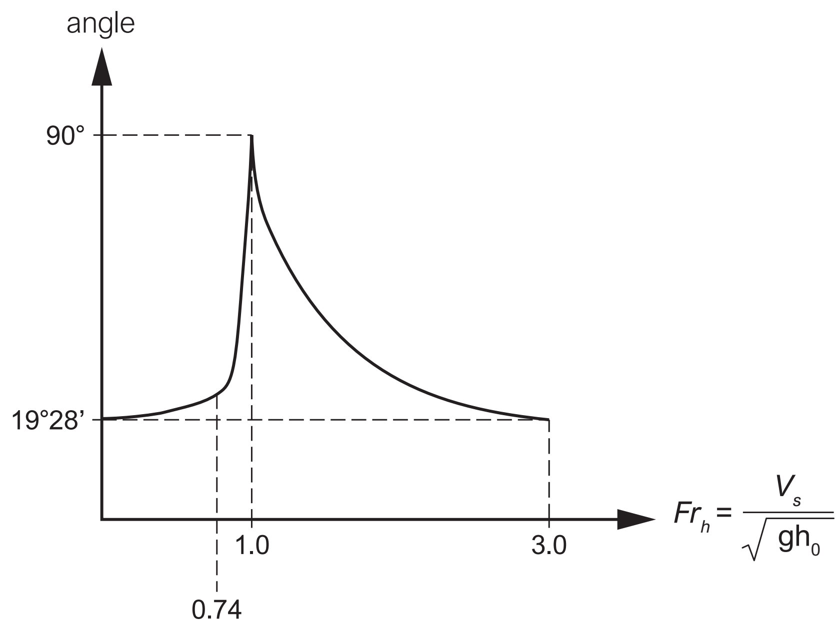


Figure 4.13: Angle θ as a function of the Froude number (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

In case of a limited channel width, reflection at the banks plays a role. It leads to extra interferences, depending on the reflection properties of the banks, the ship's speed, the ratio of the channel width and the ship length, and whether the ship sails in the centreline or eccentrically.

Furthermore, the secondary water motion is strongly influenced by the strength of the primary motion. Generally speaking, the influence of the ship-induced waves will decreases as the return current and the water-level depression increase. This means that small fast ships are responsible for most of the wave attack on the banks, whereas large slow ships cause most of the current attack.

4.2.1 Wave height of interference cusps

An empirical relation based on scale model tests (Verheij and Bogaerts, 1989) for the maximum height of the interference cusps cause by ships sailing at a moderate speed ($Fr_s < 0.8$) in relatively deep open water:

$$H_i = 1.2\alpha_i h_0 \left(\frac{y_s}{h_0}\right)^{-0.33} Fr_h^4 \tag{4.32}$$

for $h_0/L_{wi} > 0.25$, $H_i/L_{wi} < 0.14$ and $H_i/h_0 < 0.6$.

Where:

H_i	= height of interference cusps,
y_s	= distance to the side of the ship,
α_i	= coefficient between 0.85 and 1.00, depending on the type and shape of the ship,
L_{wi}	= wave length of the interfering waves.

The conditions in Equation 4.32 imply deep-water wave propagation and non-breaking waves.

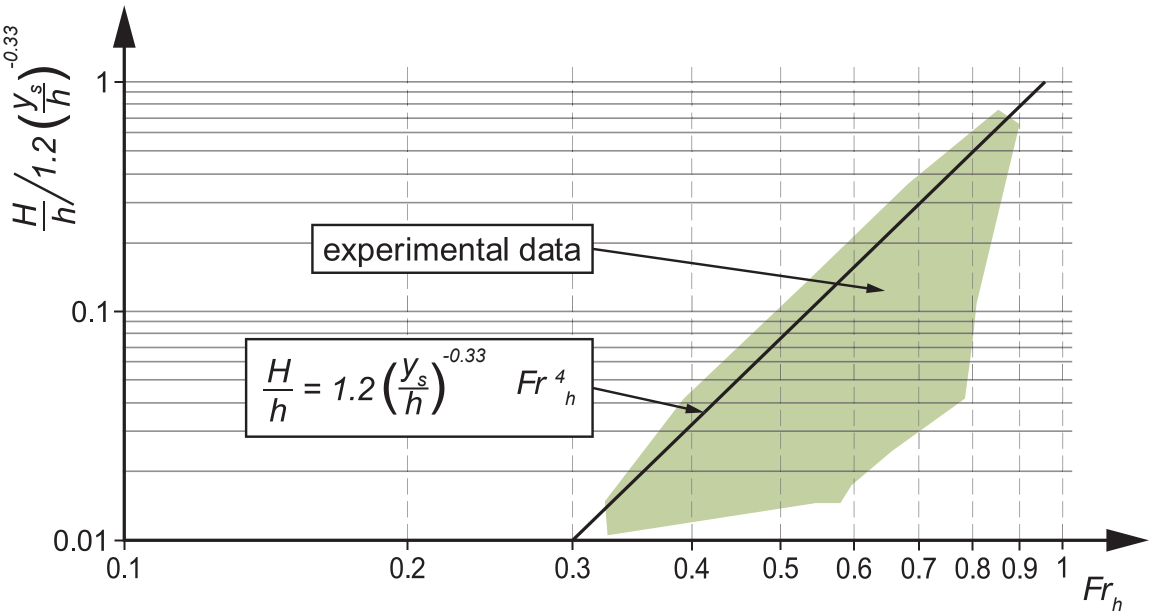


Figure 4.14: Occurring heights of interference cusps (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Numerical modelling is recommendable to determine the height of ship-induced waves (e.g. Doorn et al., 2002); also see Section 4.6.

4.2.2 Wave height of transversal waves

The height of the transversal waves around the sailing axis can be described with a similar empirical relationship, but now the relevant distance is the one between the wave crest and the ship's stern:

$$H_t = 4.0h_0 \left(\frac{x_t}{h_0}\right)^{-0.5} Fr_h^4 \tag{4.33}$$

for $h_0/L_t > 0.25$, $H_t/L_t < 0.14$ and $H_t/h_0 < 0.6$.

where:

H_t	= height of transversal waves
x_t	= distance behind the ship
L_t	= wavelength of the transversal waves.

Tests have demonstrated that a relation exists between the wave height H_t and the ship's speed, namely:

$$H_t = \gamma_t \cdot \frac{V_s^2}{g} \tag{4.34}$$

Figure 4.15 visualises this relation. The value of γ_t varies between 0.085 and 0.170 with an average value of 0.154.

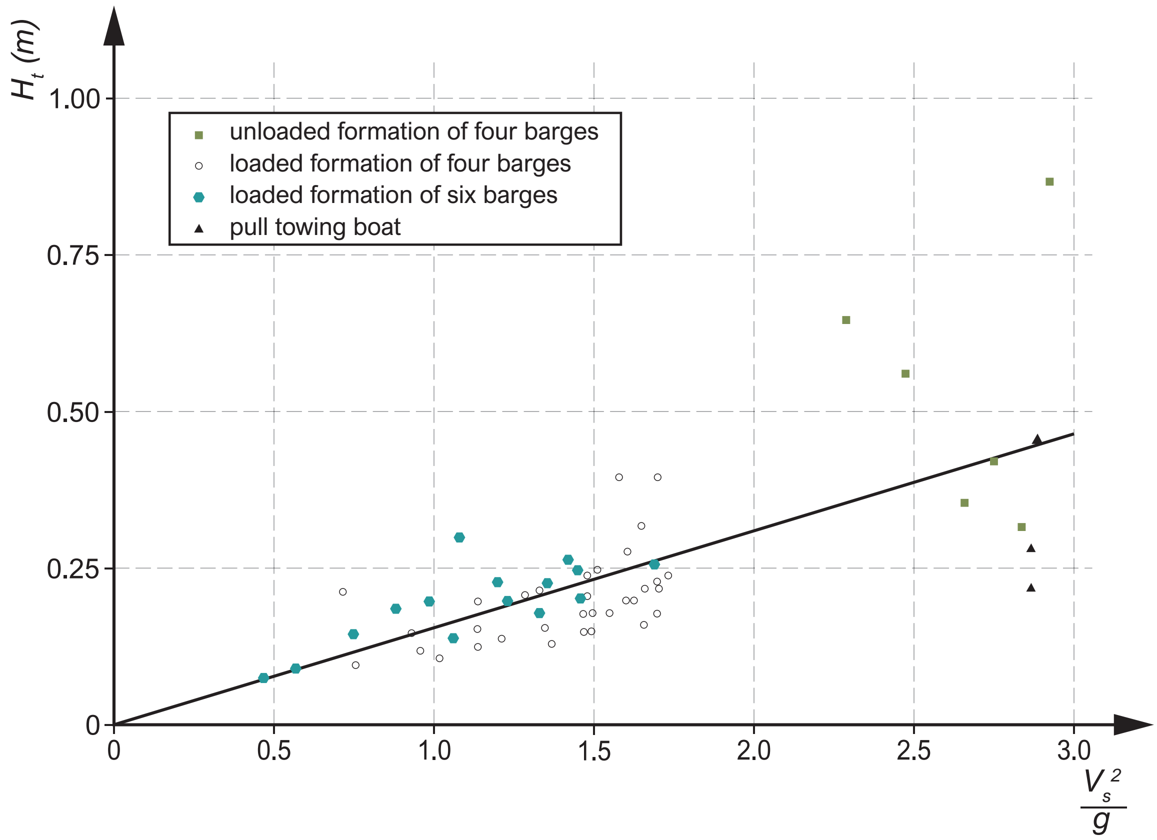


Figure 4.15: Height of transversal waves (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

4.2.3 Wave length of the divergent waves

The wave length of the transversal waves on deep water follows from Equation 4.28. The divergent waves are propagating under an angle ϕ with the navigation direction (Figure 4.13). The propagation speed of these waves is therefore $V_s \cos\phi$ and the deep-water wave length follows from:

$$L_d = \frac{2\pi}{g} V_s^2 \cos^2 \phi \tag{4.35}$$

The propagation speed of the cusps is also equal to $V_s \cos\phi$, so the distance between consecutive cusps is equal to the wave length of the divergent waves. The direction of propagation of the cusps is perpendicular to the cusp line, so in deep water under an angle of (90°- 19°28')/2 = 35°16' with the navigation direction of the ship. Since cos 35°16' = 0.82, the distance between two consecutive cusps becomes:

$$L_{wi} = 4.2 h_0 Fr_h^2 \tag{4.36}$$

and the propagation speed of the cusp is 0.82 V_s. The return period of the cusps at a fixed point is

$$T_{wi} = 5.1 h_0 Fr_h \tag{4.37}$$

4.2.4 Fast ferries

The wave pattern changes for Froude numbers greater than 0.85, as the hydrodynamic conditions change from sub-critical via critical to super-critical. Figure 4.16 through Figure 4.18 show examples of this transition.

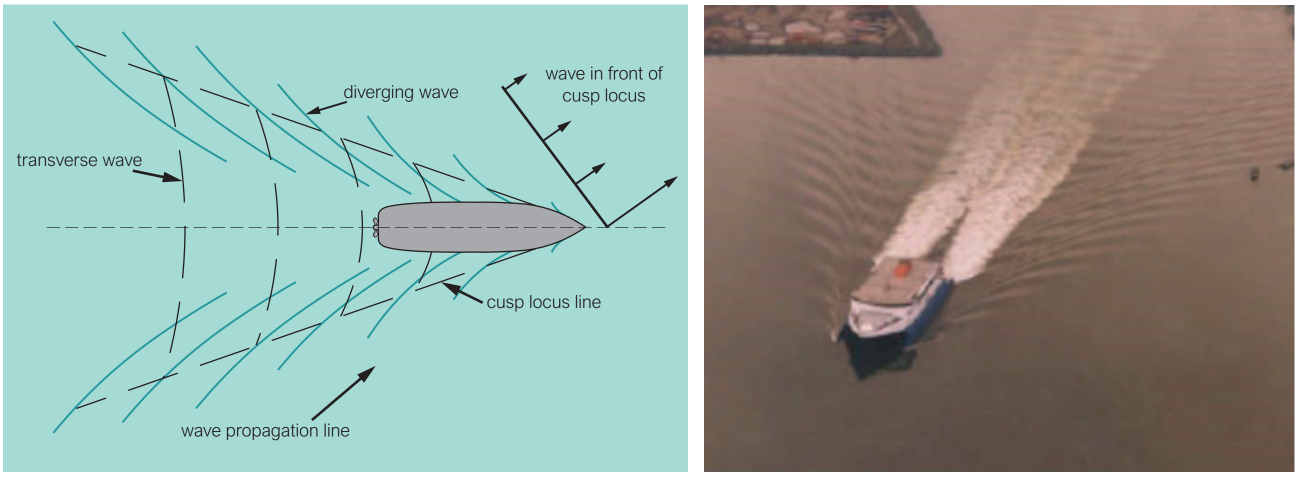


Figure 4.16: Planview and aerial photograph of catamaran with sub-critical wave pattern (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

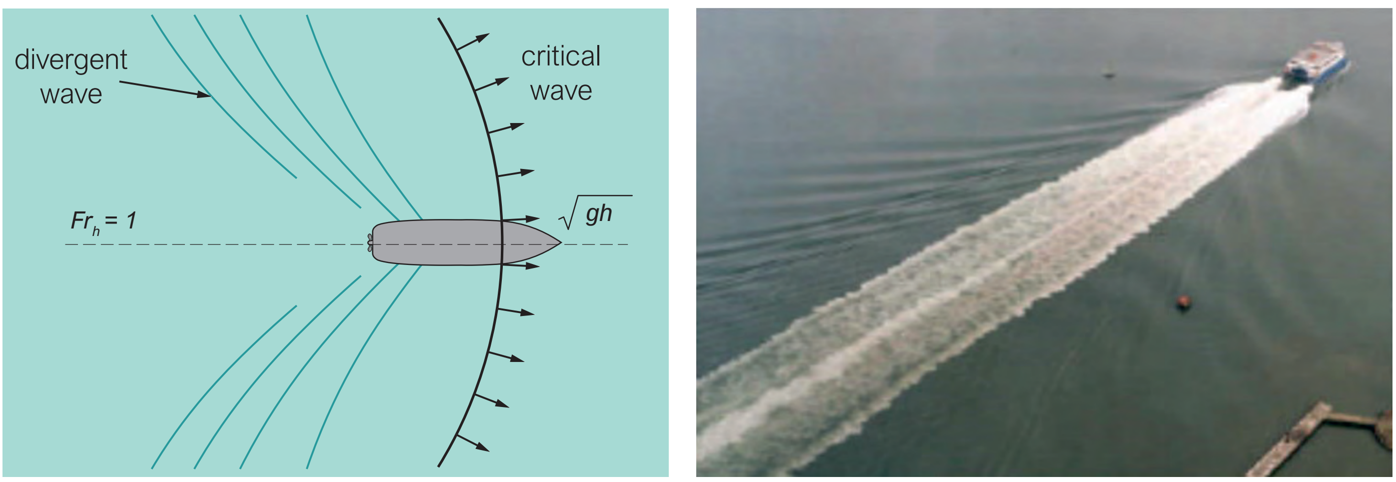


Figure 4.17: Planview and aerial photograph of catamaran passing critical conditions (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

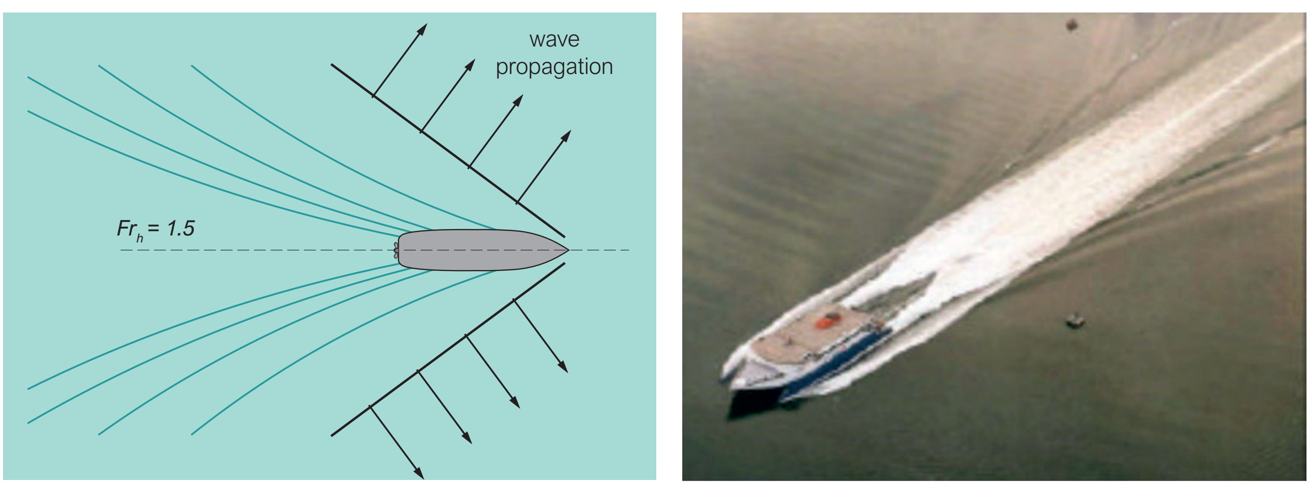


Figure 4.18: Planview and aerial photograph of catamaran with super-critical wave pattern (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The waves caused by these fast ferries may cause hindrance to moored vessels and other sailing vessels. Figure 4.19 shows that the highest waves are generated at Fr_h-values around 1, when conditions change from subcritical to supercritical. Then wave resistance is maximal, and so are the generated waves.

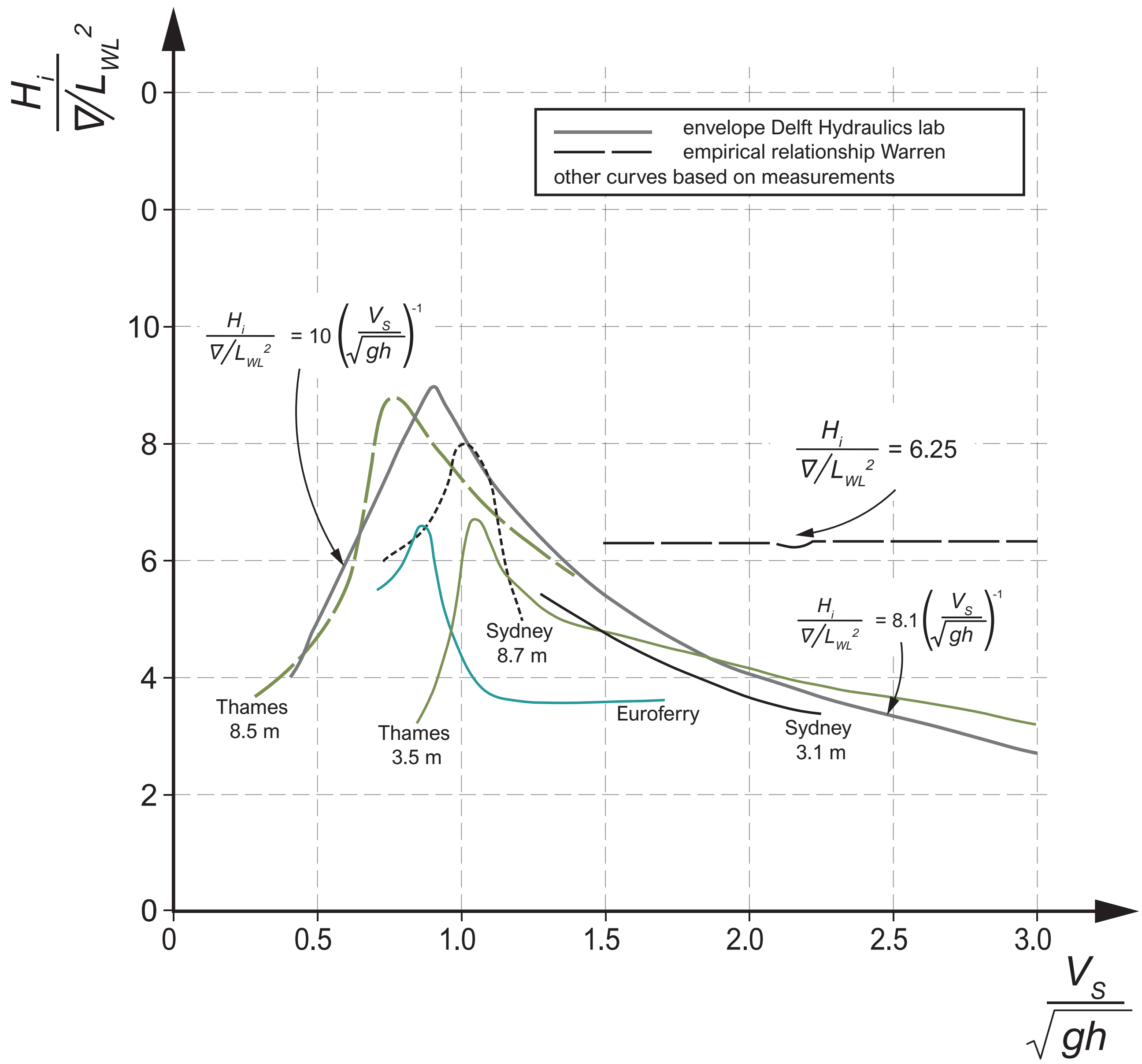


Figure 4.19: Measured wave heights of fast ferries (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

From literature study on waves generated by fast ferries, Delft Hydraulics (1994, 1998) found the following equations for the wave height:

$$Fr_h \leq 0.9: \;\; H_i = 10\frac{\nabla}{L_{WL}^2}Fr_h \tag{4.38}$$

$$Fr_h \geq 0.9: \;\; H_i = 8.1\frac{\nabla}{L_{WL}^2}Fr_h^{-1} \tag{4.39}$$

with $Fr_h = \frac{V_s}{\sqrt{gh_0}}$ and

L_{WL} = length of a ship on the water line (m)
∇ = water displacement (m^3)

The maximum wave height occurs for $Fr_L = 0.4$ (or Fr_h about 1.0) with $Fr_L = \frac{V_s}{\sqrt{gL_{WL}}}$:

$$H_i = (7.75 \pm 1.25)\,\frac{\nabla}{L_{WL}^2} \tag{4.40}$$

The characteristic wave periods of super critical waves are 8 to 9 seconds.

4.3 Propeller and thruster jets

As ships become larger, the transport network needs to be adapted. Harbour basins have to be deepened, quay walls lengthened, approach channels and other waterways widened and deepened. Moreover, the increased engine power leads to problems with bottom protection in harbours and at berths. The induced jets cause higher flow velocities and thus larger forces on existing bottom protections, if any. PIANC report 180 (PIANC, 2015) provides detailed information on how to deal with flow velocities, required bed protection or scour depth.

An additional development aggravating this problem is that many modern ships not only have main propellers at the rear of the ship, but also bow and stern thrusters perpendicular to the vessel's axis. These facilities allow the ship to manoeuvre without the help of a tugboat. They are used especially for manoeuvres such as berthing and de-berthing. The main propeller at the rear predominantly produces a forward thrust, but can help manoeuvring by changing the direction of the rudders. Figure 4.20 shows a diagram of a cross section of the bow of a sea-going ship with a side view of a bow thruster and an indication of the velocities in the jet it produces.

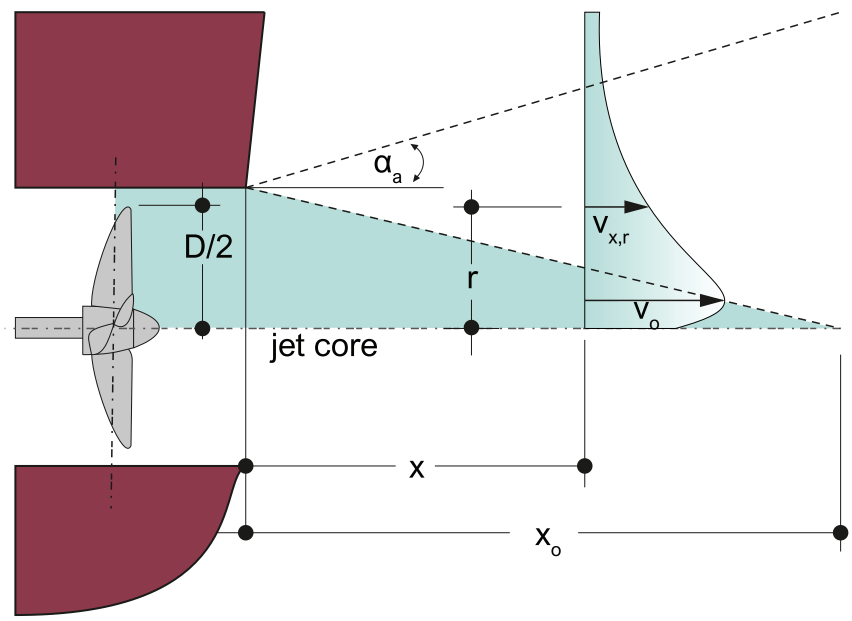


Figure 4.20: Bow thruster jet (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The force produced by the bow thruster, combined with its distance to the centre of gravity of the ship, results in a large moment of forces that causes the front of the ship to turn away from the quay, for instance. After this, the main propellers are used for forward thrust in order to sail away. The increased size and power of thrusters and propellers causes jet velocities for which the bottom of the berth and the harbour basin have not been designed (Figure 4.21). This can lead to damage and failure of the bottom protection and severe bed erosion, with quay wall failure as a possible consequence.

Inland vessels are equipped with much smaller propulsion systems. Size and power vary widely and depend on the type of vessel and the navigation conditions, e.g. width and depth of the waterway and the presence of hydraulic structures such as locks. Ship types to be distinguished are: conventional cargo vessels, container vessels, push-tow units, passenger ships, recreational boats and service boats such as tugs and patrol vessels.

In principle, all computation methods are based on the assumption that the propeller jet can be schematized as a submerged free jet discharging out of an orifice into an infinite fluid, and use the relevant equations for the zone

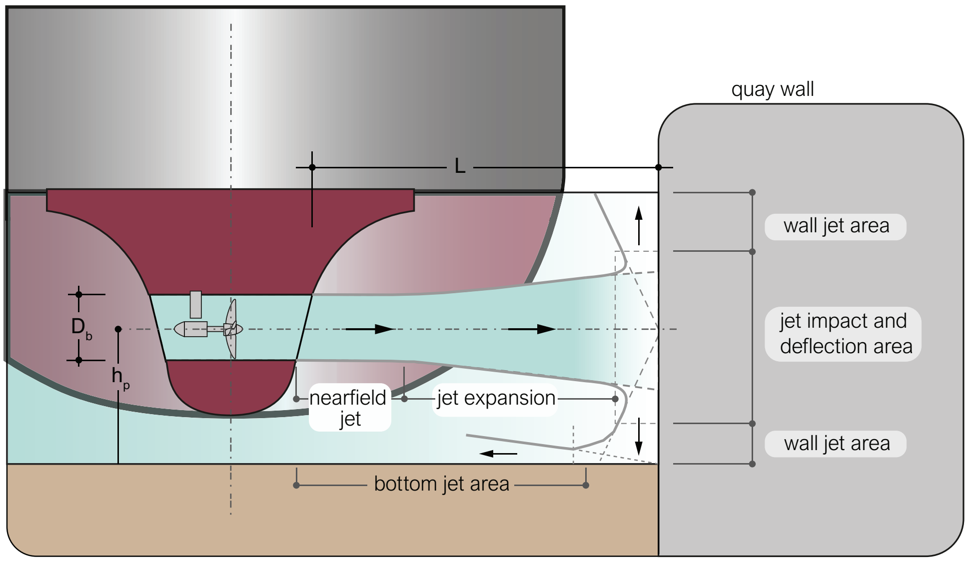


Figure 4.21: Thruster jet in the vicinity of a quay wall (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

of established flow presented by Albertson et al. (1950):

$$V_{axis} = \frac{V_0 D_p}{2Cx} \tag{4.41}$$

$$V_{x,r} = V_{axis} \exp\left[-\frac{r^2}{2C^2x^2}\right] \tag{4.42}$$

where:

V_{axis}	= flow velocity in the axis of the jet $[m/s]$,
V_0	= efflux velocity $[m/s]$
$V_{x,r}$	= flow velocity in the jet at location x, r $[m/s]$
D_p	= diameter of a free jet or propeller $[m]$
x	= horizontal distance from the propeller $[m]$
r	= radial distance from the jet axis $[m]$
C	= coefficient [-]

Albertson et al. (1950) determined a value of 0.081 for the coefficient C. Equation 4.42 describes a distribution of the flow velocity around the jet axis and applies to the zone of established flow. Closer to the orifice, in the nearfield zone, the flow has not yet established and different formulae should be used.

Note that a propeller jet differs at certain points from a free jet, e.g.

- higher turbulence levels due to propeller-induced rotation and whirl,
- reduced velocities in the centre of the jet core, due to the presence of the shaft, and
- shorter zone of flow establishment.

Outflow velocity

Blaauw and Van de Kaa (1978) present the following equation for the outflow velocity, known from maritime engineering:

$$V_0 = C_3 \left(\frac{f_p P_s}{\rho_w D_p^2} \right)^{0.33} \tag{4.43}$$

where:

P_s = maximum installed engine power $[W]$,
f_p = percentage of installed engine power [-], and
D_p = the propeller diameter $[m]$.

Based on information of pilots and skippers (PIANC, 2015), the following values are recommended for f_p:

- thruster: $f_p = 1.0$, because always 100% of the installed power will be applied;
- main propellers: $f_p = 0.05$ to 0.15, but values up to 0.40 cannot be excluded.

Typical values for the coefficient C_3 are 1.17 for ducted propellers and 1.48 for free propellers, but other values are mentioned in literature.

When substituting for a free (i.e. non-ducted) propeller a value of $C_3 = 1.48$ and taking $D_p = 1.41 \cdot D_0$, with D_0 the effective jet diameter, the coefficient of proportionality for a free propeller becomes 1.17. As this is the same as for a ducted propeller with $C_3 = 1.17$ and $D_p = D_0$, Blaauw and Van de Kaa (1978) presented one equation for both types of propellers:

$$V_0 = 1.15 \left(\frac{f_p P_s}{\rho_w D_0^2} \right)^{0.33} \tag{4.44}$$

In practice we only know D_p, so calculations have to be made with that quantity, irrespective of its uncertainty. If even D_p is unknown, the propeller diameter can be estimated by $D_p = 0.6$ to 0.7 D_s, where D_s is the ship's draught. The main propeller diameter of inland vessels is mostly 1.8 m and the bow thruster diameter 0.8 m.

On the basis of an inventory of the engine power installed in inland vessels, Verheij (2010) found the following relationships between the average installed main propeller power and the wet surface area of the hull:

$$P_{main} = 0.66 L_s (B_s + 2D_s) \tag{4.45}$$

In 90% in inland vessels, the installed power is less than about 1.25 P_{main}. Outflow velocities of 6 to 8 m/s are normal.

Flow distribution within the jet

To determine the velocity distribution in a jet, there are basically two approaches, a German and a Dutch one. For the German approach we refer to the PIANC WG 180 manual (PIANC, 2015). The Dutch approach is based on research by Blaauw and Van de Kaa (1978) and Verheij (1983). They found a value of the constant C of 0.18, which is much larger than the value of 0.081 found by Albertson et al. (1950). This higher value corresponds with a faster spreading of the jet.

Substitution in Equation 4.41 and Equation 4.42 yields for the flow velocity in the jet axis:

$$V_{axis} = 2.8 \frac{V_0 D_p}{x} \tag{4.46}$$

and for the velocity profile perpendicular to the axis:

$$V_{x,r} = V_{axis} \exp \left[-15.4 \frac{r^2}{x^2} \right] \tag{4.47}$$

In unconfined shallow water, the flow velocity at the bed follows from these two equations and the distance h_p of the propeller axis from the bed. Given the Gaussian character of $V_{x,r}$, the flow velocity distribution at the bed is likely to be Gaussian, as well, with the maximum below the propeller axis.

Test results largely agree on where the maximum flow velocity at the bed occurs (Verheij (1983): $x/h_p = 4.5 \div 8$; Rajaratnam (1976): $x/h_p = 4 \div 10$). If we assume $x/h_p = 6$, Equation 4.46 yields:

$$V_{b,max} = 0.3 \frac{V_0 D_p}{h_p} \tag{4.48}$$

Multiple jets

In the case of two propellers and a limited UKC, the distance y_p between the propellers and the distance h_p from each propeller axis to the bed determine the velocity at the bed. According to Verheij (1983), superposition of jets is allowed in the cases considered here. Blokland (1997), however, derived for two propellers:

$$V_{max} = V_{single} \qquad h_p/y_p < 0.578 \tag{4.49}$$

$$V_{max} = 0.43 \text{ to } 0.61 V_{single} D_0/r \qquad 0.578 < h_p/y_p < 1 \tag{4.50}$$

$$V_{max} = V_{single}\sqrt{2} \qquad h_p/y_p > 1 \tag{4.51}$$

with $r = \sqrt{h_p^2 + y_p^2}$

Other propulsion systems

In addition to the well-known main propellers, other propulsion systems are used in inland navigation. Examples are water jets, mainly applied in ferries and rescue vessels, and Voith Schneider (cycloidal drive) propellers, mainly used in tugs and ferries. We will discuss water jets in more detail here, because this type of propulsion can generate outflow velocities up to 25 m/s if the full engine power is applied. Hardly any bed protection can withstand such high flow velocities.

Water jet propulsion The axial pump driving the jet is more efficient than a propeller, and therefore produces higher speeds with the same energy expenditure and less vibration and noise. The jets are usually installed in pairs. Manoeuvring is possible by differential power application or by turning one of the jets forward (Figure 4.22). Maximum power can amount to 26 MW for sea-going ferries, yielding outflow velocities up to 25 m/s, whereas conventional propellers reach at most 8 – 10 m/s.

Verheij and Stolker (2007) derived the following set of formulae for the Kamewa water jet:

$$V_0 = 0.92 \left[\frac{f_p P_s}{\rho_w A_0} \right]^{0.33} \tag{4.52}$$

$$V_{axis} = 12.4 V_0 x^{-1.17} \tag{4.53}$$

$$V_{x,r} = V_{max} \exp\left[-92.75 \frac{r^2}{x^2} \right] \tag{4.54}$$

in which A_0 is the cross-sectional area of the outflow opening. The square opening of Kamewa jets is 1 m^2. If the outflow opening differs not much larger or smaller than 1 m^2, it can be translated into an equivalent circular opening with diameter D_{eq}. In that case Equation 4.53 can be replaced by:

$$V_{axis} = 10.8 V_0 \left(\frac{D_{eq}}{x} \right)^{1.17} \tag{4.55}$$

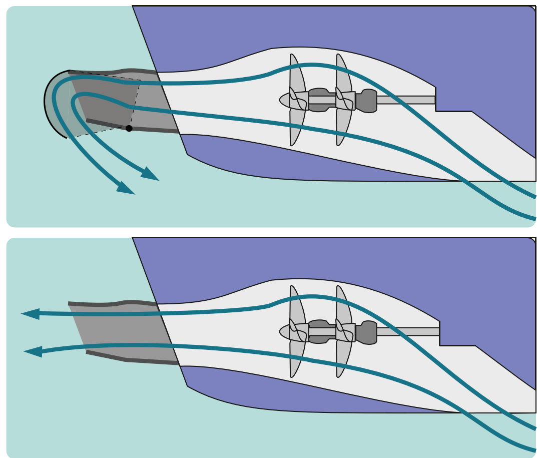


Figure 4.22: Water jet propulsion (reworked from: Wikimedia Commons, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0)

Particularly dangerous for the stability of mobile beds is the possibility to direct these jets downwards. Kamewa jets can reach an angle of about 45 degrees (Figure 4.23), but other catamarans are equipped with jets that can be directed vertically.

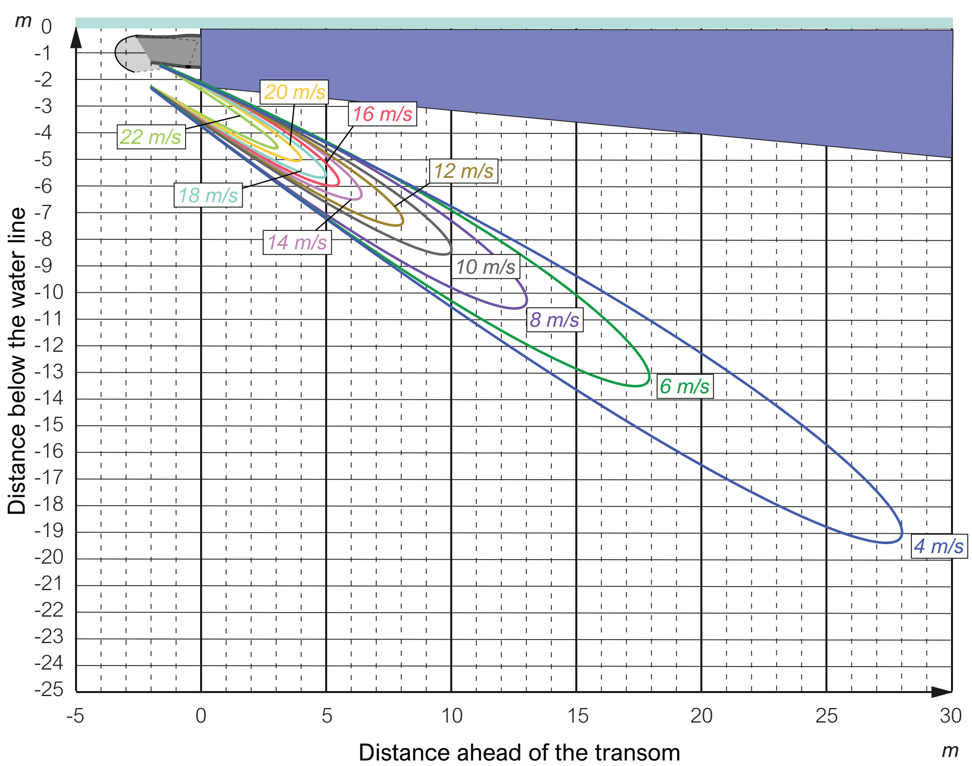


Figure 4.23: Flow velocities in a downward-directed Kamewa water jet (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

4.4 Other phenomena related to sailing ships

4.4.1 Stern waves

The primary water motion is described as consisting of a return current around the ship and a related water-level depression over the width of the waterway. The transition between the undisturbed water level in front of the vessel and the water-level depression beside the ship is called the front wave and the transition at the stern, between the water level depression and the undisturbed water level behind the vessel is called the stern wave. Both waves take the form of a sloping water surface (Figure 4.24).

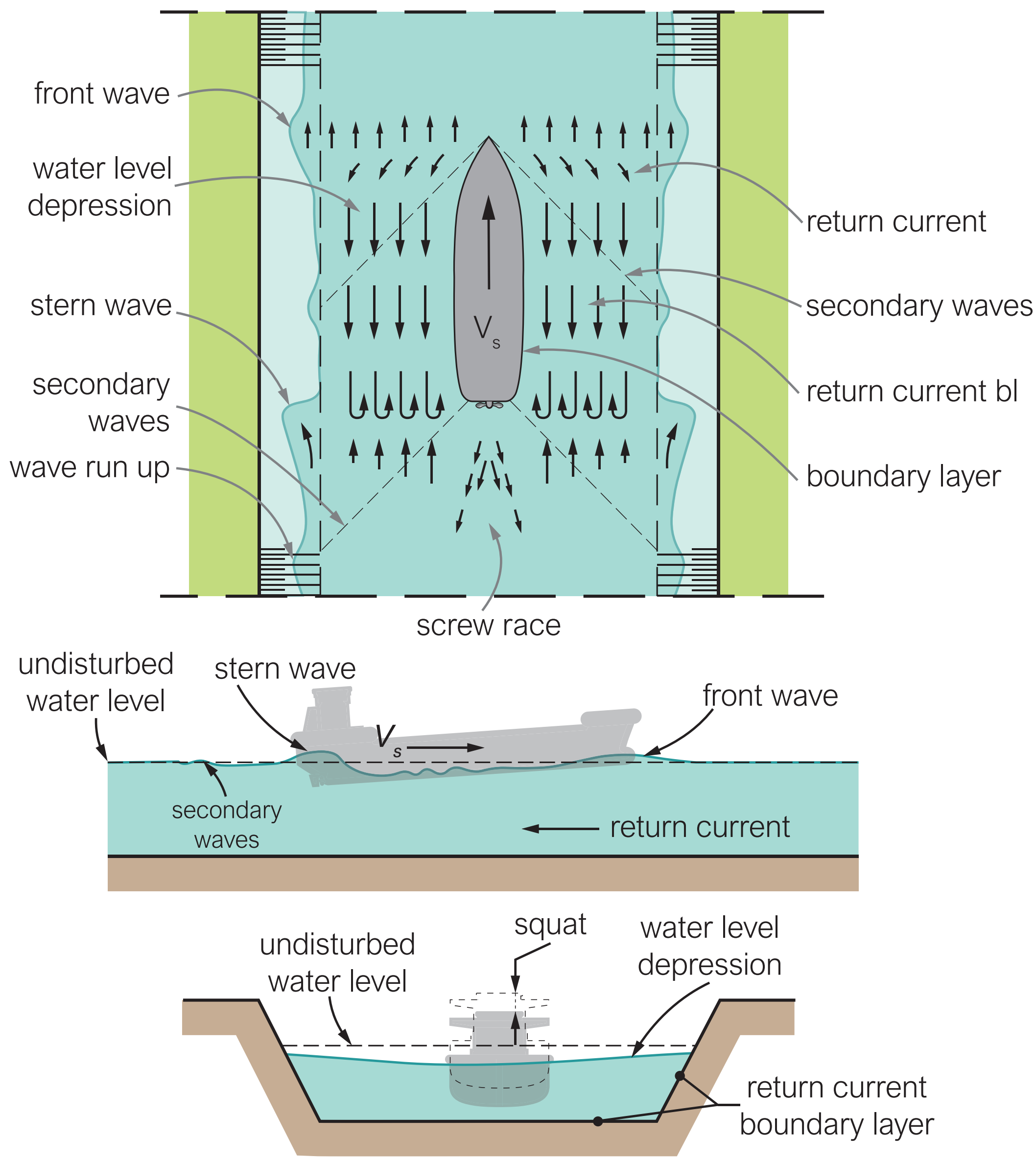


Figure 4.24: Ship-induced water motion (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The height of the front wave is slightly greater than the water-level depression. The stern wave is the transition between the water-level depression and the normal water level behind the ship. This area is locally influenced by the water level depression associated with the propeller jet.

Both the front wave and the stern wave cause current velocities ahead of and directly behind the ship. The direction of these currents is the same as the navigation direction of the ship itself. The stern wave causes an attack at the bank slope protection which can be the determining factor for stability, especially for trapezoidal profiles. It becomes stronger as the ship sails closer to the bank.

The maximum water level elevation z_{max}, the water level gradient i_{max} and the maximum velocity u_{max} due to the stern wave follow from (Delft Hydraulics, 1988):

$$z_{max} = (1.5 \div 2.0)z \tag{4.56}$$
$$i_{max} \leq 0.1 \div 0.15 \tag{4.57}$$
$$u_{max} = V_s(1 - \Delta D_{50}/z_{max}) \tag{4.58}$$

where D_{50} = characteristic grain diameter (m) and Δ = relative density of the the bank protection material.

Note that the celerity of the front of the stern wave is equal to the ship speed. Equation 4.58 gives the maximum velocity of water particles in the stern wave.

As the ship speed increases, the stern wave may eventually break, depending on the local water depth (Figure 4.25). Then i_{max} is larger than 0.1 to 0.15 and the wave breaking causes an extra attack on the bank protection.

On top of this, propeller jets can create another attack on bed and bank protections. This is especially the case in bends and near unloading and holding quays. The jet is very turbulent and velocities can be very high (up to 10 m/s). When manoeuvring or starting from stationary, a vessel may therefore cause serious scour and protection failure.

The current velocity behind the stern wave, the so-called 'wake', is mainly caused by the return of water from the propeller jet. In extreme situations, with large sailing speeds and a small UKC ($h_0/D_s < 1.2$) a very strong wake may occur. The maximum wake velocity in this situation might grow to a velocity even larger than the maximum return current velocity under the ship, as has been shown in experiments.

Figure 4.25: Stern wave breaking on a bank (images by Bundesanstalt fr Wasserbau (BAW) are licenced under CC BY-NC-SA 4.0).

4.4.2 Transverse gradients in the water motion

So far, we have assumed the primary water motion to be uniform over the cross-section. This is only true if A_c/A_s is smaller than 5 (or W_s/B_s smaller than about 12). For larger values a gradient will occur and the water level depressions and return current velocities will decrease as the distance to the ship increases.

Based on potential flow theory one may estimate the transverse distribution of the current velocities and the water level depression, but at present this is done with numerical models (Figure 4.26).

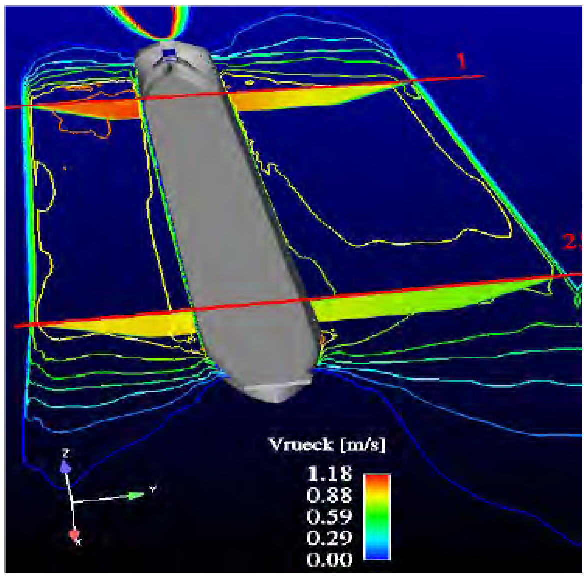


Figure 4.26: Computed gradient in return current next to the ship (image by Bundesanstalt für Wasserbau, Karlsruhe is licensed under CC BY-NC-ND 4.0).

4.4.3 Flow velocities underneath the ship keel

Tunnels and pipelines crossing navigation canals or rivers cannot always be buried deep below the bed and may require a cover layer to protect the structure against the induced water motions below the ship keel (Figure 4.27). Also bed protections in harbours and approaches to locks are influenced by water motions caused by ships sailing over them (CIRIA; CUR; CETMEF, 2007).

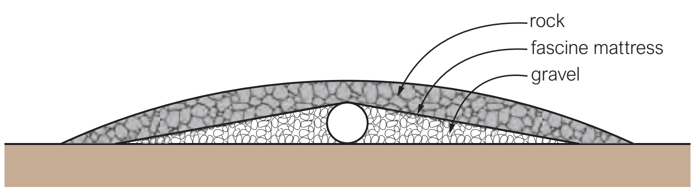


Figure 4.27: Protected pipeline crossing (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The flow field underneath the ship's keel cannot be computed as if it were one-dimensional. The maximum flow velocity occurs below the bow where the height available to the flow is less than the under keel clearance. Figure 4.28 explains why.

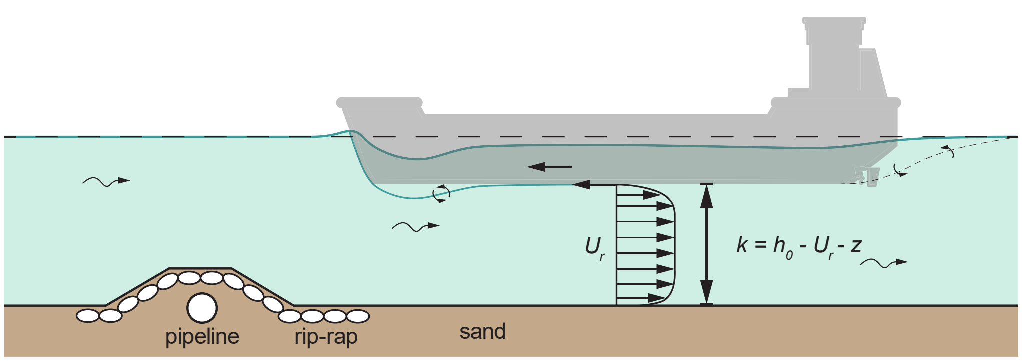


Figure 4.28: Schematic of the flow between ship and channel bed (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Equation 4.59 gives a first estimate of the flow velocities underneath a ship (Dorst et al., 2016):

$$U_{rb} = cU_r \tag{4.59}$$

where $c = 1.5$ to 2.0

Research at Delft Hydraulics (Stolker and Verheij, 2006) resulted in an improved version of the co called Maynord equation (also see Figure 4.29):

$$\frac{U_{rb}}{V_s} = 1.07\left(\frac{B_s}{h_0}\right)^{0.08}\left(\frac{D_s}{h_0}\right)^{1.82} \tag{4.60}$$

in which U_{rb} is the return current velocity just outside the bed boundary layer. This velocity can be used to calculate the bed shear stress and the sediment transport rate. In case of a coarse sediment bed (sand or gravel) the transport gradients determine the local erosion. In case of finer sediment (fine sand, silt or mud) the shear stress directly determines the erosion rate:

$$\frac{dz_b}{dt} = \frac{M}{\rho_s g}\left(1 - \frac{\tau_b}{\tau_{cr}}\right) \tag{4.61}$$

$$\tau_b = \frac{1}{2}c_f \rho_w U_{rb}^2 \tag{4.62}$$

in which:

z_b = bed level with respect to a fixed reference level $[m]$,
t = time $[s]$,
M = erosion coefficient $[kg/(ms^3)]$
τ_{cr} = critical shear stress for erosion $[N/m^2]$
τ_b = actual bed shear stress $[N/m^2]$
c_f = friction coefficient [-]

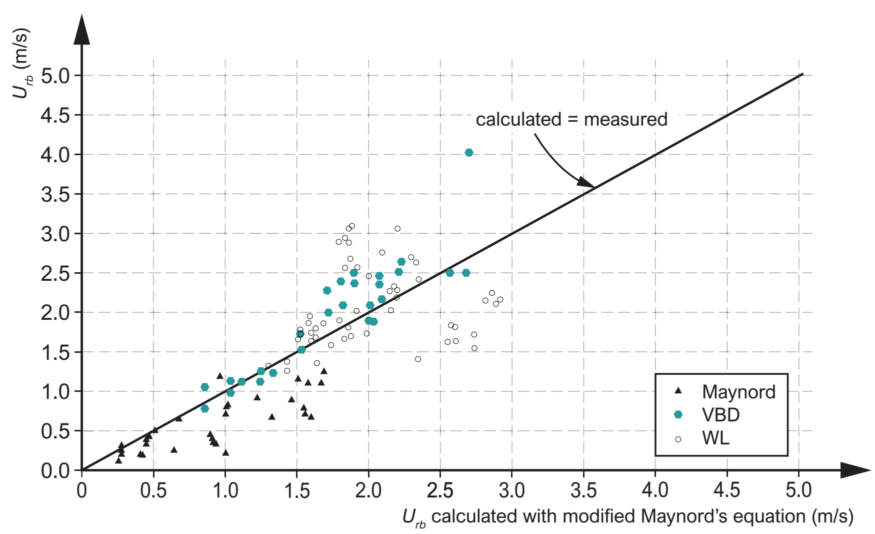


Figure 4.29: Computed and measured flow velocities under the keel (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

3-D numerical simulation models such as Delft3D can also be used to predict sediment transport and bed level effects of navigation. This concerns not only the effect of an individual vessel on the bed below it, but also the larger-scale effect of navigation on the sediment transport capacity of a river, for instance.

4.4.4 Ship-induced water motions in rivers and groyne fields

So far we have assumed the channel banks to be straight and closed. Many regulated rivers, however, are bordered by groynes and groyne fields. The presence of groynes influences the flow, also outside the groyne fields. Figure 4.30 shows the flow pattern in a groyne field induced by a passing push-tow unit. It shows that if a large vessel or convoy passes a groyne at short distance this may result in strong eddies, in particular directly after passage of the stern (Figure 4.31).

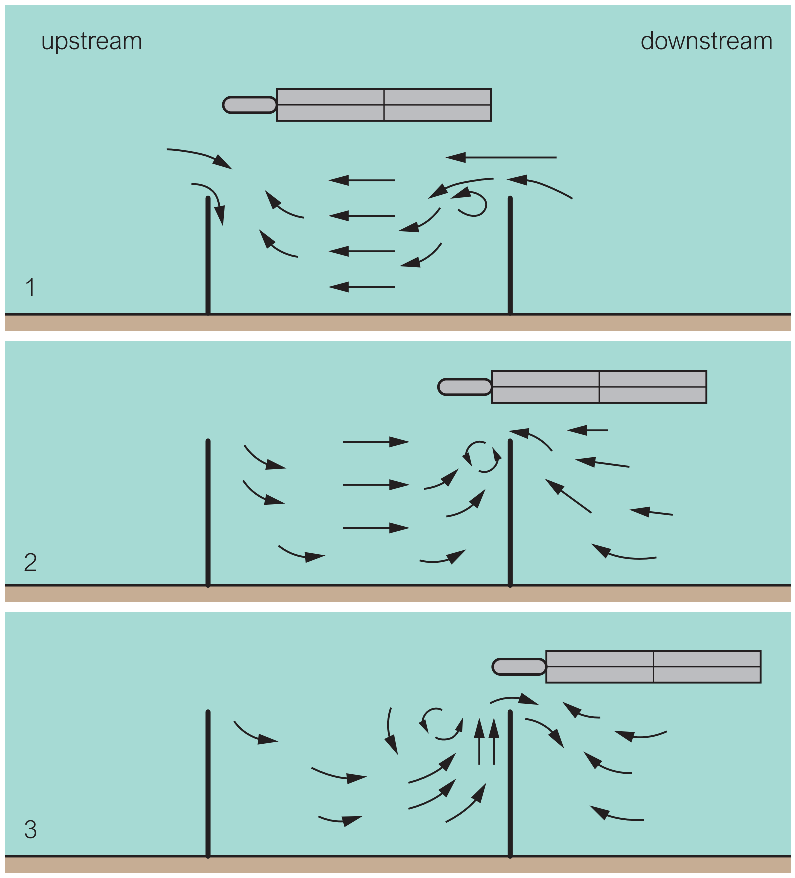


Figure 4.30: Flow in a groyne field induced by a passing four-barge unit (modified from Brolsma, 1988, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

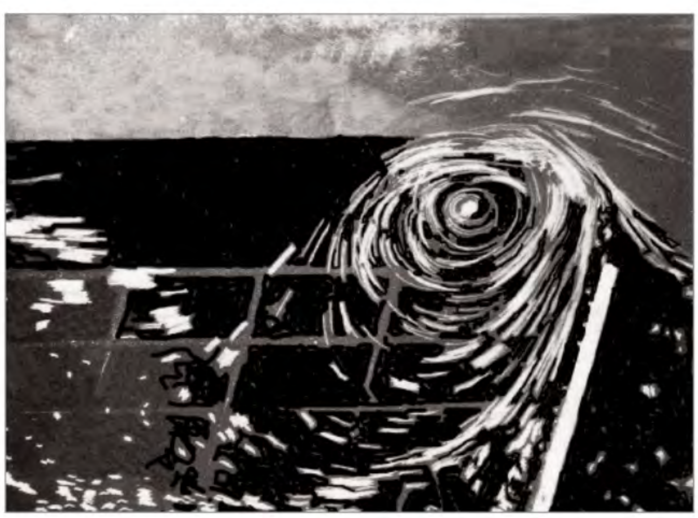


Figure 4.31: Eddy downstream of a groyne directly after passage (to the right) of a push-tow unit (Deltares (1987), verslag modelonderzoek Q93/Q576).

Clearly, the flow velocities around the head of a groyne can be very high. A first estimate of the velocities in a groyne field follows from the empirical equation (Termes et al., 1991; CIRIA; CUR; CETMEF, 2007):

$$\frac{|U_{local}|}{|U_c + U_r|} = \alpha \left(\frac{h_0}{h_{ref}} \right)^{-1.4} \tag{4.63}$$

in which:

U_{local} = maximum flow velocity at a location in the groyne field [m/s],
U_c = average flow velocity in the river [m/s],
U_r = average return velocity in front of the groyne head [m/s],
α = coefficient depending on the location in the groyne field [-],
h_0 = average water depth in the river [m], and
h_{ref} = average water depth in the river at the discharge at which the groynes submerge [m].

For the groyne fields along the Dutch Rhine branches, the value of α varies between 0.2 and 0.6, but this does not necessarily apply to other rivers. The highest values are directly downstream of the head of a groyne.

4.4.5 Hydrodynamic phenomena during overtaking

When a vessel is overtaking another, their return currents and the water-level depressions will reinforce each other. Therefore the water level will decrease more between the two ships than between ship and bank. The ships will experience more resistance, and as the overtaking manoeuvre proceeds, they will be drifting towards each other due to the difference in hydrostatic pressure (Figure 4.32).

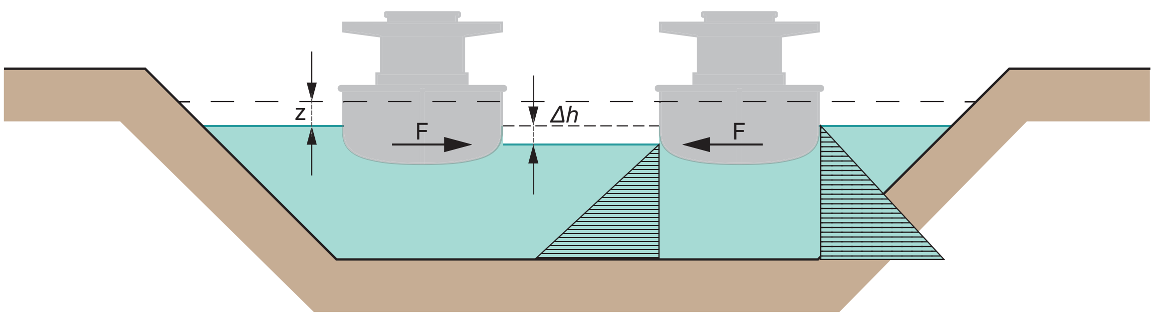


Figure 4.32: Hydrostatic pressure during overtaking (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

In an overtaking manoeuvre the navigator must pay close attention in order to stay in control, although the risks involved depend on the space available, of course.

The overtaking manoeuvre can be successfully completed if the ship to be overtaken strongly reduces her speed and the overtaking ship sails at an adjusted speed, so as not to be sucked against the other ship. However, reducing the speed of the ship to be overtaken must not lead to insufficient rudder pressure for manoeuvrability. In practice, overtaking is only feasible if the difference in speed between the two ships is more than 5 km/h.

The overtaking ship has to overcome two hydrodynamic barriers during the manoeuvre. The first barrier to overcome is at the start of the manoeuvre (Figure 4.33). The overtaking ship suddenly encounters a much smaller wet cross-section, with area $(A_c - A_{s,1} - W_s z_1)$ due to the space occupied by the ship to be overtaken $(A_{s,1})$ and the water level depression (z_1) it causes. Moreover, the overtaking ship has to negotiate the extra return current $(U_{r,1})$ caused by the ship to be overtaken.

The smaller flow section and the extra return current reduce the limit speed of the overtaking ship $(V_{lim,2})$, whereas it has to remain higher than the actual speed of the ship to be overtaken. In reality, this is usually not a problem, because, due to the extra water level depression and return current, the speed of the ship to be overtaken will strongly decrease once the overtaking ship is next to her.

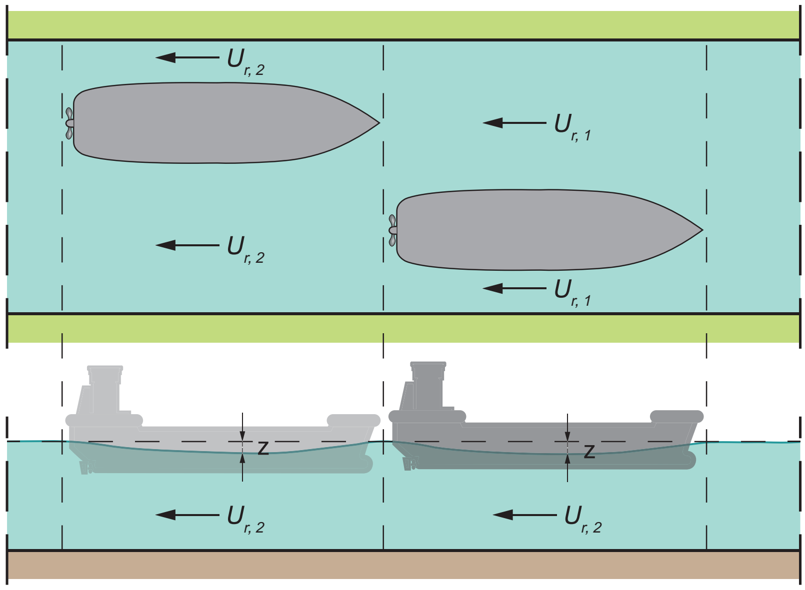


Figure 4.33: First barrier when overtaking (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The second barrier occurs when the bow of the overtaking ship has just passed the other ship's bow (Figure 4.34). The bow of the former is then in an area of water level depression caused by itself, while the stern is still in the area of combined water level depression. The ship has to overcome the extra trim this causes, which requires extra power. If the overtaking ship does not dispose of this, she will lose speed and the overtaking manoeuvre will slow down or even fail.

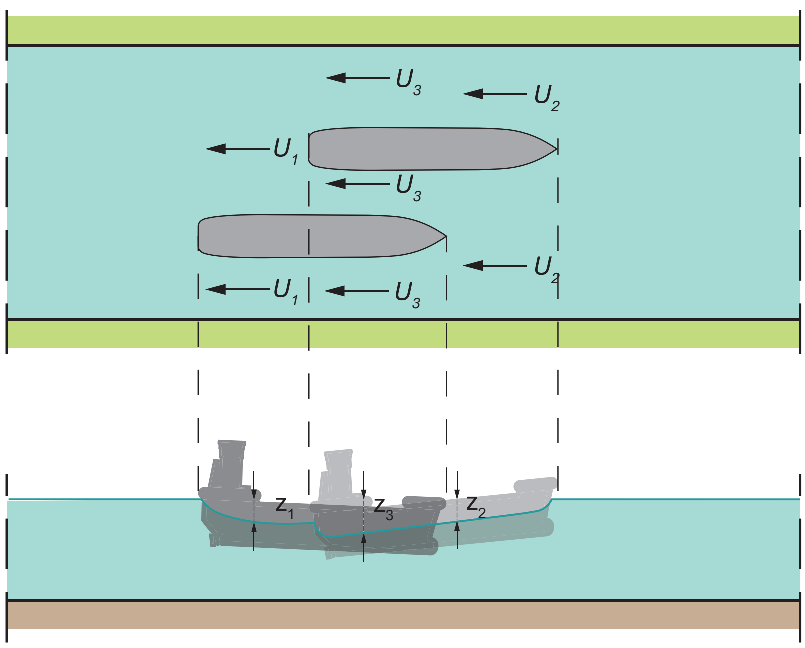


Figure 4.34: Second barrier when overtaking (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The opposite applies to the ship that is overtaken: the bow is in an area of combined water level depression and the stern has only the ship's own water level depression. This generates a positive trim and a forward directed force, which will cause an increase of the ship's speed.

It may happen that the two ships come to sail as one system with the same speed, the so-called group speed. In that case the overtaking ship drags the slower ship along in their common water level depression. This may cause the overtaking manoeuvre to fail. For the overtaking manoeuvre to be successful, the slower ship must to reduce its speed.

The channel cross-section should be dimensioned for situations in which such a speed reduction is necessary. This may require a significantly larger profile than in the situation where no overtaking is allowed. Note that, nevertheless, the overtaking ship must still have sufficient power to overcome the second barrier.

In principle, it is possible to compute the individual ship speeds, the duration of the overtaking manoeuvre and the hydrodynamic phenomena (return current and water level depression) with the Schijf method. Janssen and Schijf (1953) give results of a number of laboratory tests on overtaking. Nowadays, it is more convenient to use Computational Fluid Dynamics (CFD) models for this purpose, of which Section 4.6 gives an example.

4.4.6 Water motions in locks due to emptying or filling of the lock chamber

Emptying or filling of a lock chamber can be realized in three ways:

1. by opening sluices in the gates (possible in all three variants);
2. by opening the valves in bypass or longitudinal drains that discharge water through one or more openings in the chamber walls or the chamber floor;
3. by slightly lifting or tilting the gate (a vertical lift or pivot gate, for instance) and allowing water to pass by.

When filling the chamber the energy dissipation inside the chamber is considerable, as the flow decelerates rapidly. This can cause great inconvenience to the vessels in the chamber, especially if it is fi

lled fast. When emptying the chamber, i.e. the outgoing flow accelerates and suppresses turbulence, which is less of an inconvenience to the vessels. When decelerating outside the chamber, the flow is highly turbulent, again, and may cause erosion. To prevent this, bed protection structures are applied.

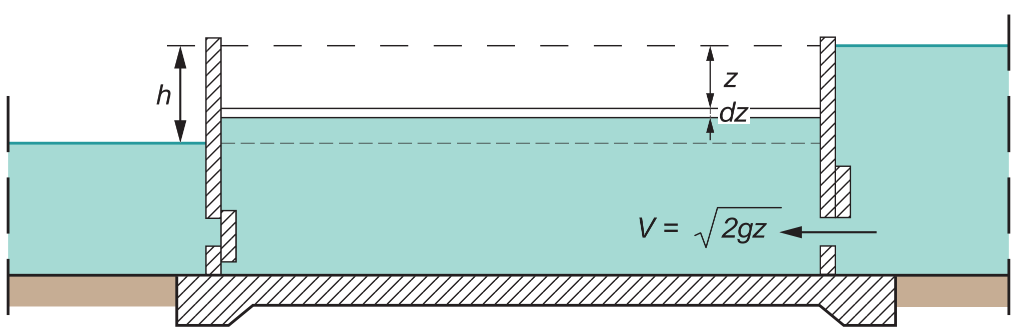


Figure 4.35: Chamber filling by means of sluices in the gates (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Filling and emptying time in case of slowly varying water levels

If the sluice (opening area A_{sl} [m^2]) is suddenly opened, the water discharge entering the chamber, the time-dependent filling discharge $Q_f(t)$, will be

$$Q_f(t) = mA_{sl}\sqrt{2gz(t)} \tag{4.64}$$

in which the discharge coefficient m depends on the shape and curvature of the discharge opening and will vary between 0.6 and 0.9. If the surface area of the chamber is A_{ch} [m^2], mass conservation requires:

$$A_{ch}dz = -mA_{sl}dt\sqrt{2gz} \tag{4.65}$$

(note that z decreases as the chamber fills up). Integrating this over time, with initial condition

$$z(t=0) = H \tag{4.66}$$

yields (Figure 4.36):

$$z(t) = \left[\sqrt{H} - \frac{mA_{sl}\sqrt{2g}}{2A_{ch}}t\right]^2 \tag{4.67}$$

Then the total filling time T (when $z = 0$) follows from:

$$T = \frac{2A_{ch}\sqrt{H}}{mA_{sl}\sqrt{2g}} \tag{4.68}$$

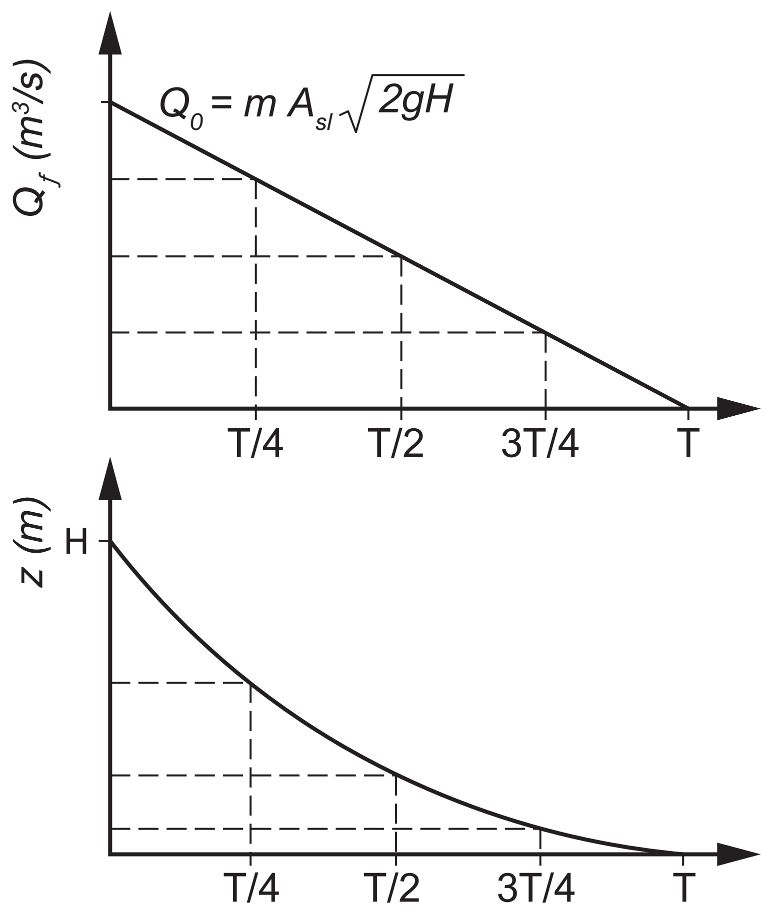


Figure 4.36: Slow chamber filling process if the sluice is opened suddenly (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Filling and emptying time in case of translatory waves

In the previous paragraphs we assumed the level in the lock chamber to rise gradually over the entire chamber area. In reality, however, a translatory wave will run up and down the chamber if the sluice is suddenly opened. As a consequence, the lock chamber will be filled in 'slices' (Figure 4.37).

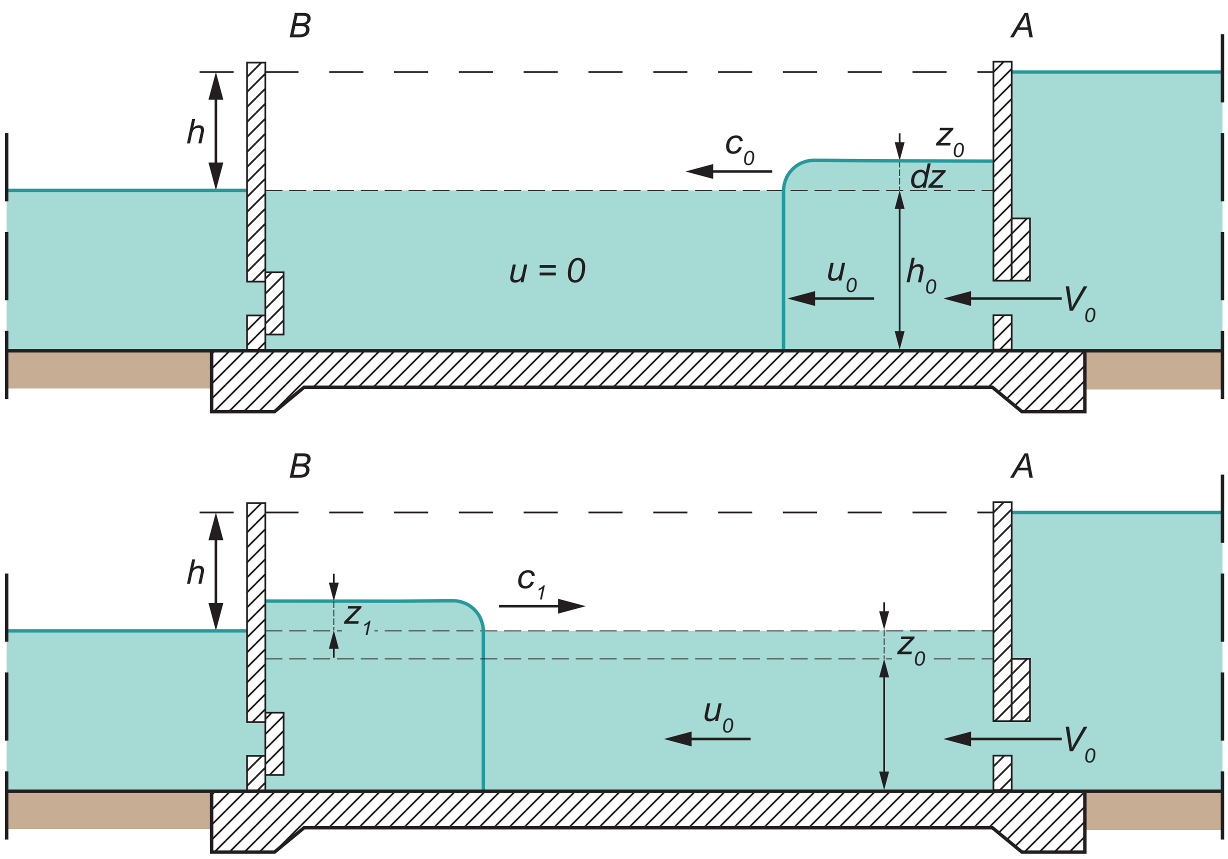


Figure 4.37: Translation wave during lock filling (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

At time $t = 0$ a positive translatory wave of height z_0 begins to propagate from A to B (Figure 4.37). Initially, there will be an equally high negative wave propagating from the other side of the gate away from the lock. The lock approach area is assumed to be so much wider than the lock entrance, that this effect can be ignored after some time. Then the propagation speed of the first translatory wave in the chamber is

$$C_0 = \sqrt{g(h_0 + z_0)} \tag{4.69}$$

The discharge through the sluice determines the height of the wave. Mass conservation requires:

$$Q_f = C_0 z_0 W_l = m A_{sl} \sqrt{2g(H - z_0)} \tag{4.70}$$

When this wave reaches the end of the lock, it bounces against gate B. The returning wave of height z_1 has a propagation speed

$$C_1 = \sqrt{2g(h_0 + z_0 + z_1)} \tag{4.71}$$

where the wave height follows from mass conservation, again:

$$Q_f = C_1 z_1 W_l = m A_{sl} \sqrt{2g(H - z_0)} \tag{4.72}$$

et cetera.

Figure 4.38 shows schematically the filling process due to a translatory wave. Note that the sluice discharge only changes every time the bounced wave reaches gate A again. Also note that the wave height decreases as the lock chamber fills up.

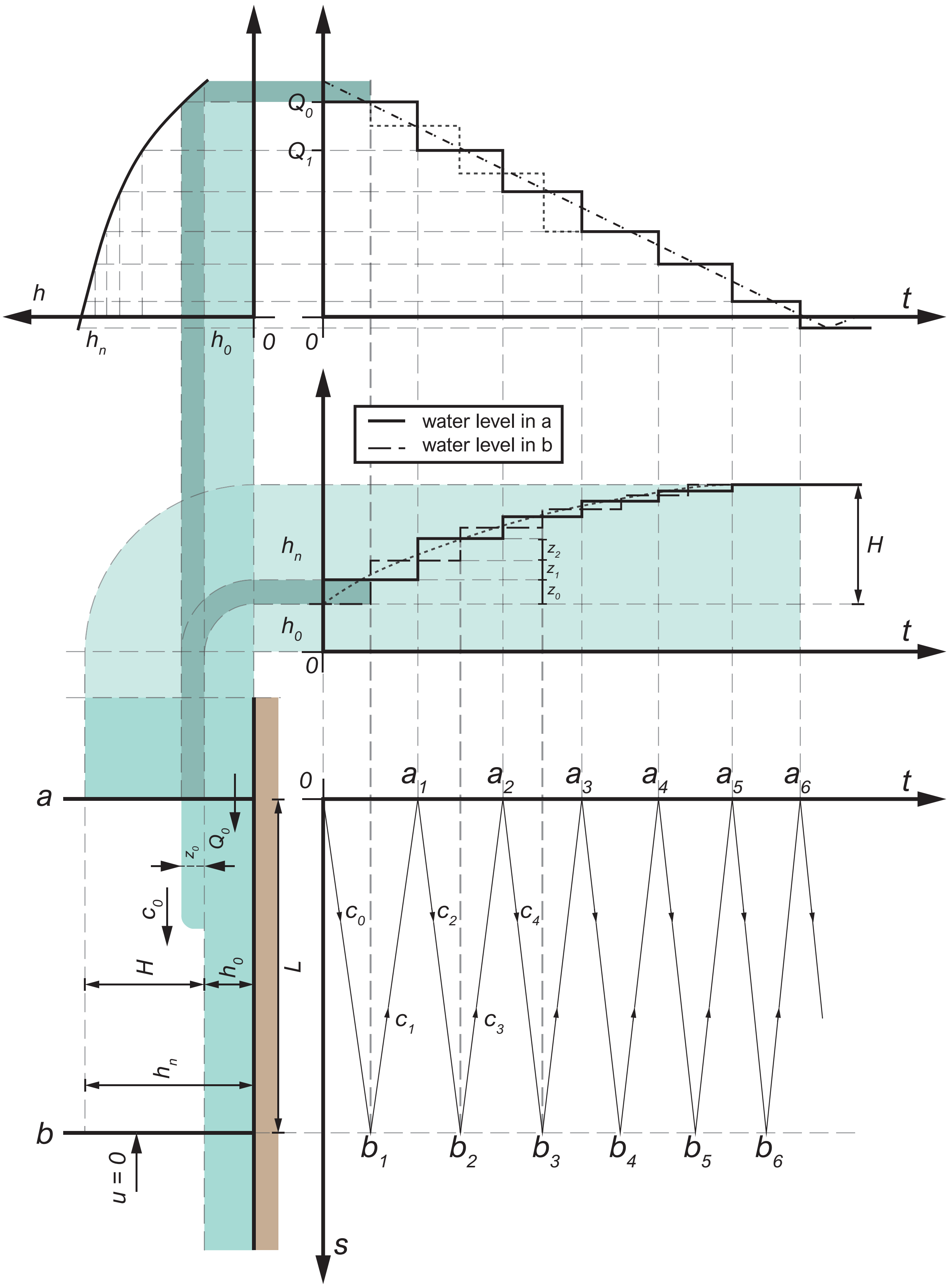


Figure 4.38: Lock chamber filling with translation waves (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

If there are ships in the lock chamber, a completely different situation occurs. A complex system of hydraulic forces on the ships creates large hawser forces, extra reflections of the translation wave against the ships and a more complex velocity field (Figure 4.39).

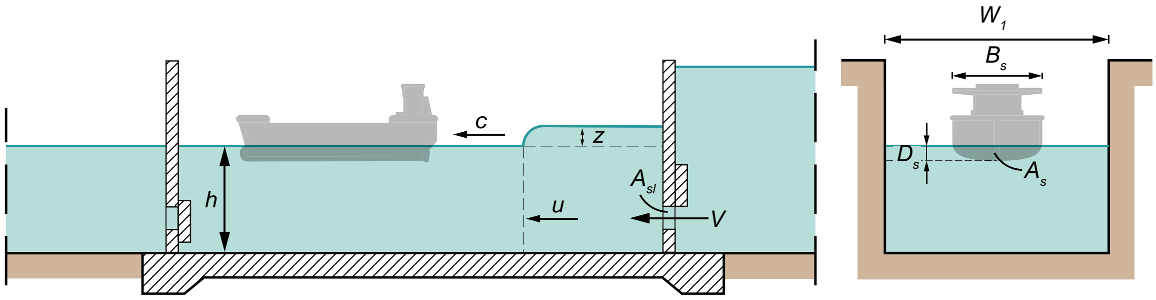


Figure 4.39: Translation wave in a lock chamber with a ship (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Even though the situation is more complex, the translation waves are recognisable in the time-variation of the hawser forces: they keep on changing sign. more or less at the frequency of the wave front passages (Figure 4.40). Further see Part IV – Section 4.3 for how these hawser forces can be dealt with.

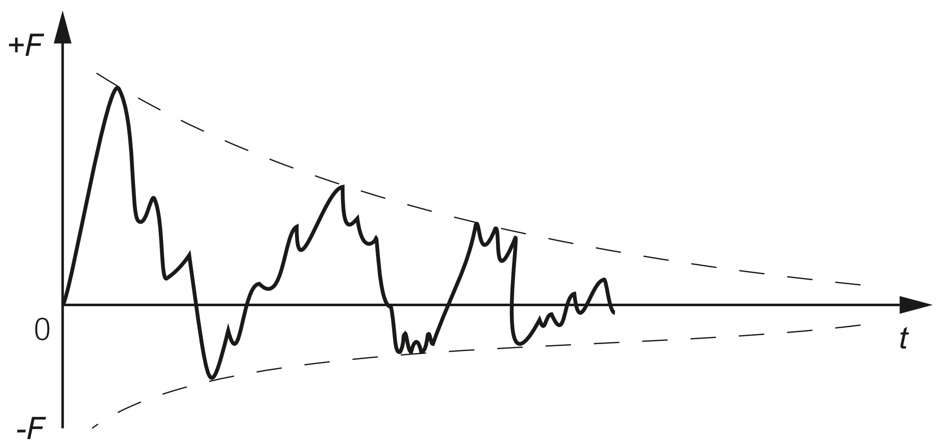


Figure 4.40: Observed time-evolution of a hawser force (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Filling or emptying the chamber by gradually opening the sluice

Hawser forces can be reduced by opening the sluice more gradually. If the sluice is opened at a constant speed, a rectangular opening will increase linearly with time (Figure 4.41).

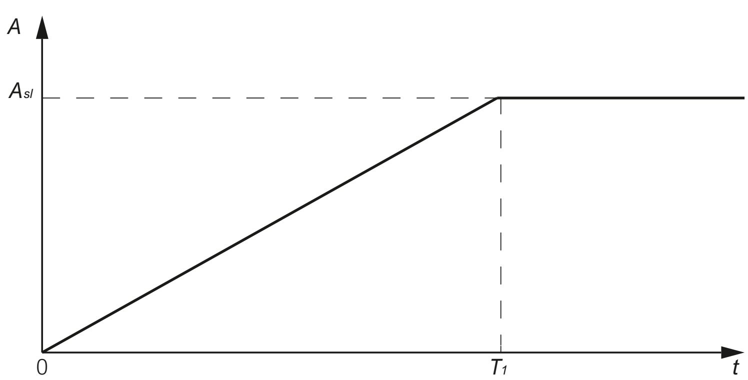


Figure 4.41: Linear sluice opening process (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

If the sluice is opened linearly over time T_1 and the chamber fills evenly without translation waves, continuity requires (see Figure 4.37 for symbol definitions):

$$A_{ch}dz = -mA_{sl}\frac{t}{T_1}\sqrt{2gz}dt \tag{4.73}$$

whence, with initial condition (Equation 4.67):

$$z(t) = \left(\sqrt{H} - \frac{mA_{sl}\sqrt{2g}}{4A_{ch}T_1}t^2\right)^2 \tag{4.74}$$

for $0 < t < T_1$. At the end of the sluice opening procedure we have

$$z(T_1) = \left(\sqrt{H} - \frac{mA_{sl}\sqrt{2g}}{4A_{ch}}T_1\right)^2 \tag{4.75}$$

The remaining level difference $H - z(T_1)$ is filled up in the same way as in the case of sudden opening,

$$z(t) = \left(\sqrt{zT_1} - \frac{mA_{sl}\sqrt{2g}}{2A_{ch}}(t - T_1)\right)^2 = \left(\sqrt{H} - \frac{mA_{sl}\sqrt{2g}}{2A_{ch}}(t - \frac{1}{2}T_1)\right)^2 \tag{4.76}$$

Then total filling time becomes:

$$T = \frac{T_1}{2} + \frac{2A_{ch}\sqrt{H}}{mA_{sl}\sqrt{2g}} \tag{4.77}$$

So the total filling time increases with half the sluice opening time, as compared to the case of a sudden sluice opening.

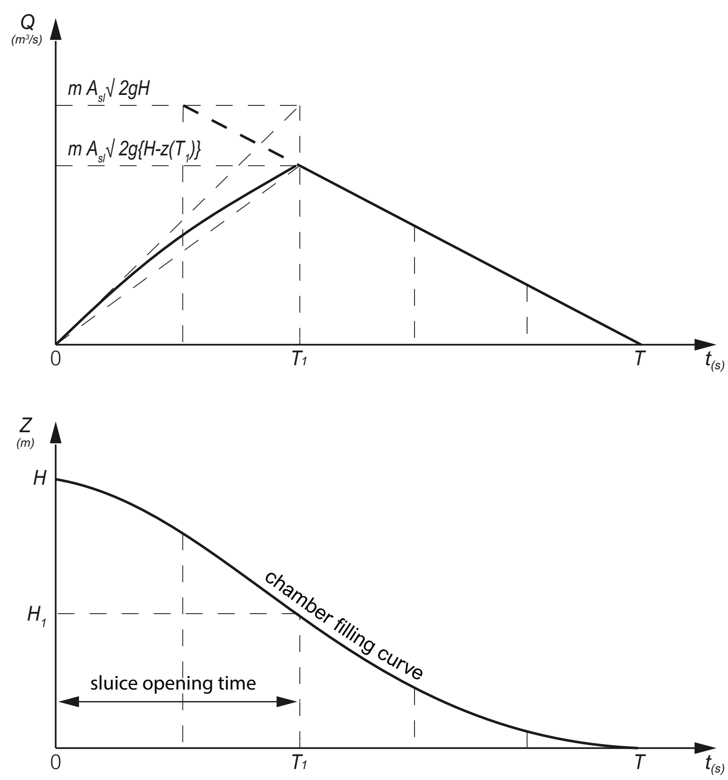


Figure 4.42: Lock chamber filling with a gradually opened sluice (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 4.42 shows the time evolution of the filling process. Figure 4.36, Figure 4.38 and Figure 4.42 all show that the filling rate considerably slows down towards the end of the process. That is why in practice the gates are opened before the entire head difference has been levelled out. This can save a significant amount of time.

4.4.7 Ship-induced translation waves

In the transition between the lock approach and the relatively narrow lock a ship encounters changes in return current, water-level depression and resistance. A sudden transition in cross-sectional area gives rise to the following phenomena:

- the return current velocity along the ship increases significantly, as does the waterlevel depression,
- a positive translation wave enters the lock chamber;
- a negative translation wave propagates into the lock approach area.

The greater the ship's speed and the greater the transition in blockage factor, the stronger these phenomena become (see Figure 4.43 and Figure 4.44).

During the actual lock entry, the navigation speed and the associated hydrodynamic phenomena may become quite irregular (Figure 4.43). In practice, however, this gives little cause for concern as long as the blockage factor is $A_s/W_l h < 0.4$.

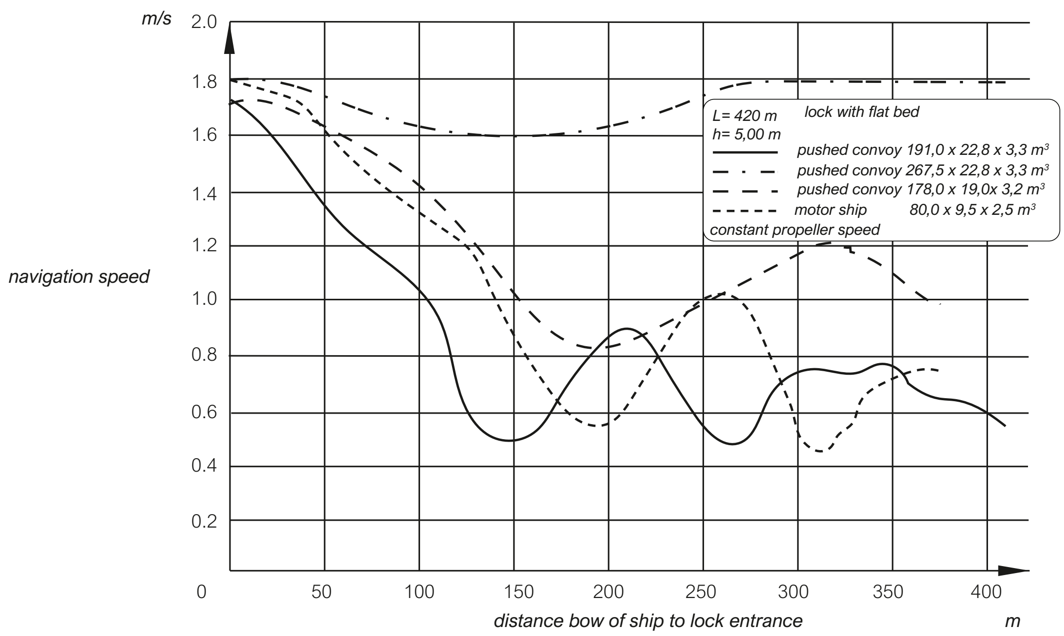


Figure 4.43: Navigation speed when approaching and entering a lock (Kooman, 1973). Image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0.

Another problem arises with loaded push convoys in push convoy locks and the largest maritime vessels in maritime locks, which can have blockage factors up to 0.8. Their initial speed (V_0) may not be too large, otherwise the translation waves created by them may cause damage to the closed gates the first time they rebound. The maximum height of the translation wave (Z_{max}) appears to be directly proportional to the square of the initial vessel speed and the ratio of the midship cross-sectional area (A_s) and the remaining cross-sectional area ($W_l h_0 - A_s$) through which the return current takes place. According to Figure 4.44, the coefficient of proportionality is approximately 1.44, so:

$$\frac{Z_{max}}{h_0} = 1.44 \frac{V_0^2}{g h_0} \frac{A_s/A_{lock}}{1 - A_s/A_{lock}} \tag{4.78}$$

in which $A_{lock} = W_l h_0$ and h_0 is the water depth in the lock chamber or above the entrance threshold, depending on the case considered.

In principle, Equation 4.78 shows some resemblance with the value z_{max} that can be computed with the Schijf method, with Equation 4.6 for a ship sailing in a canal, but instead of A_s/A_c now the value of A_s/A_{lock} is applied.

Figure 4.44: Maximum ship-induced translation wave height at the closed lock head (Kooman, 1973). Image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0.

4.5 Ship speed and ship resistance

The speed of a ship mainly depends on the resistance encountered while sailing, and of course on the installed engine power transferred by the propeller. The speed chosen is a trade-off between travelling time, transport costs and on time cargo delivery. Much research has been done on this subject, because it enables ship owners to obtain important management information, such as energy consumption and travel time per trip, and the number of ships needed for a certain throughput. Relevant research, including field tests, has been done in Germany. In the Netherlands MARIN played a significant role, though primarily focusing on optimising the shape of the ship's hull. Delft Hydraulics came up with equations to predict the ship's speed (Van de Kaa, 1978). A comprehensive overview is presented by Pompée (2015).

In principle, the ship speed on restricted water follows from:

$$P_b \eta_T = R_T (V_s + U_r) \tag{4.79}$$

in which:
P_b = effective power [kW],
η_T = total efficiency factor [-],
R_T = total resistance [kN],
V_s = ship speed [m/s],
U_r = return current [m/s].

The applied power is not the full installed power, because about 10% is used for systems on board such as lighting, heating, et cetera. Furthermore, there are various losses in the system (see Figure 4.45). The total energy loss is the sum of all individual components. The efficiency factor η_T typically has a value of 0.7.

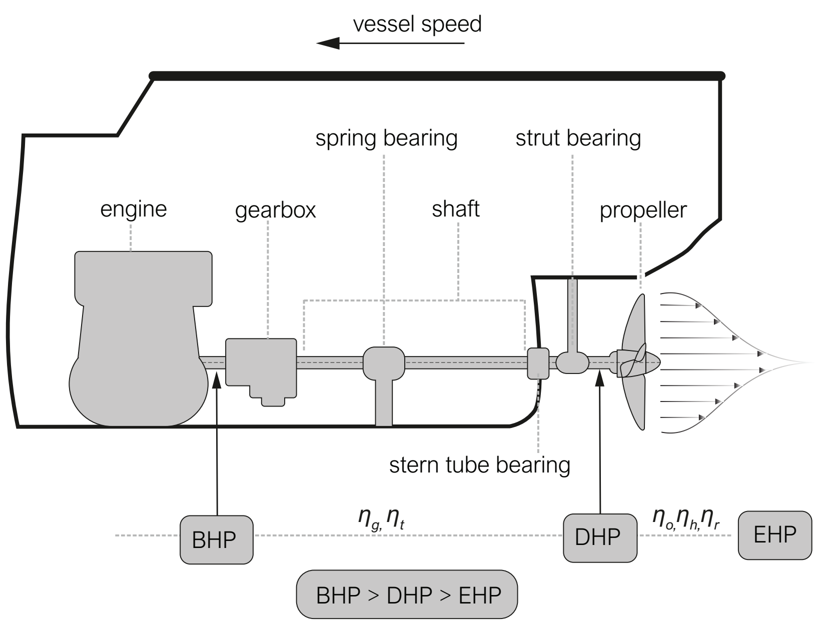


Figure 4.45: Schematic of the different power components and efficiency factors (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The total resistance R_T encountered by a sailing ship is strongly determined by the geometry of ship and waterway and the previously described interaction between the two. Especially in restricted water, most of the resistance is caused by the water movement around the ship. Sinkage and trim play a role here, but in a first approximation of the relationship between deployed engine power and ship speed we assume the sinkage to be equal to the water level depression and trim to be absent.

The resistance, expressed as a force, consists basically of two components: frictional resistance and pressure or wave resistance (Figure 4.46). There are more components, such as the resistance caused by a bulb at the bow and the resistance due to appendages such as rudders and propellers, but they are generally of secondary importance. For a detailed overview, see Part IV – Section 5.1.

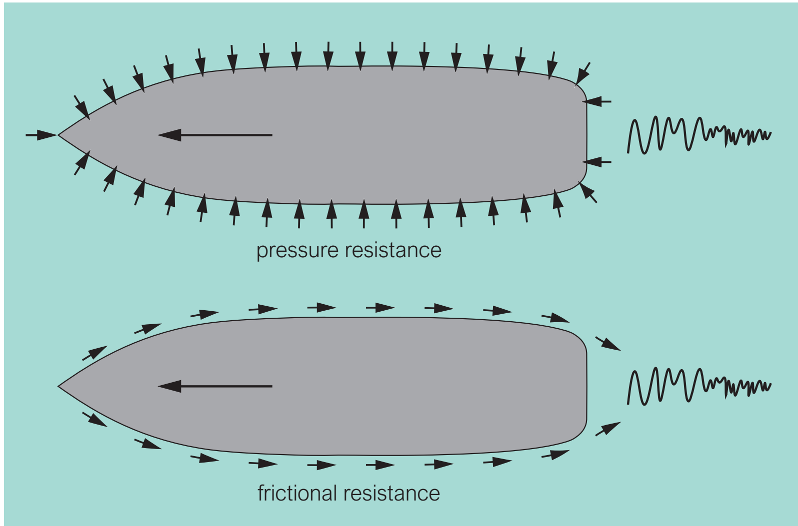


Figure 4.46: Frictional and pressure resistance (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

(a) *Frictional resistance* is caused by friction forces, acting tangentially on the surface of the submerged part of hull. If a ship sails in unconfined water without an ambient current, this part of the resistance is proportional to the ship's speed squared and its wetted surface area, S:

$$R_f = \frac{1}{2}\rho_w V_s^2 C_f S \tag{4.80}$$

In restricted water the return current and the water-level depression cause a significant part of the resistance of moving ships. This is taken into account via

$$R_f = \frac{1}{2}\rho_w (V_s + U_r)^2 C_f S \tag{4.81}$$

So here the ship's speed relative to the surrounding water is the determining factor. The friction coefficient C_f depends on parameters such as the roughness of the hull and the shape and dimensions of the ship. If no further information is available, a value of 0.002 is often a good first estimate. For old ships with a lot of fouling higher values may apply.

(b) *Pressure resistance* – is caused by differences in water pressure on the submerged part of the hull. Water pressure is omnidirectional, but the difference between bow and stern may give rise to a net longitudinal component causing resistance against the ship's forward motion. This pressure resistance is approximately proportional to the wet amidships cross-section and the ship's speed squared:

$$R_p = \frac{1}{2}\rho_w V_s^2 C_p A_s \tag{4.82}$$

The pressure resistance increases as the waterway becomes more restricted, due to the increased sinkage and trim of the ship associated with the larger water level depression. The drag coefficient C_p depends on the shape and the (underwater) dimensions of the ship. A typical value is 0.1, but values up to 0.3 have been found for loaded pusher tugs, depending on the number of push-barge units.

Van de Kaa (1978) has introduced a simplified equation to determine the total resistance R_T of push-barge units in restricted water:

$$R_T = \frac{1}{2}\rho_w \left(V_s + U_r\right)^2 C_f S + \frac{1}{2}\rho_w V_s^2 C_p A_s + \rho_w g A_s z \tag{4.83}$$

The extra term accounts for the fact that in case of a push-barge unit the propeller is at a small distance behind the barges. In case of a conventional ship the propeller is at the stern, where water-level depression is no longer present. The basic assumption is that the thrust produced by the propeller is used entirely to overcome the pressure and frictional resistances, so as not to generate the secondary hydrodynamic phenomena around the moving ship.

Resistance may also be increased if a vessel sails closely to a bank, for instance when it encounters another ship, or is overtaken by one. The return current between the vessel and the bank will increase and thereby the water-level depression and the sinkage. This slows down the vessel, commonly by some 5 to 10%. If in case of an emergency the ship has to navigate very close to the bank, the speed reduction may increase to 15 to 20%.

For conventional vessels and tugs, the total resistance can be estimated with the following set of empirical equations derived by Gebers (in Graewe, 1967):

$$R_T = \rho_w g \left(C_p A_s + C_f S\right)\left(V_s + U_r\right)^{2.25} \tag{4.84}$$

$$S = \nabla^{1/3}\left(3.4\nabla^{1/3} + 0.5L_s\right) \tag{4.85}$$

$$\nabla = C_B L_s B_s D_s \tag{4.86}$$

The block coefficient depends on the ship type. Typical values are 0.9 for conventional ships and 0.75 for tugs.

The coefficients C_p en C_f depend on the draught:

C_p = 3.5 10^{-3} for a loaded ship,
C_p = 2.0 10^{-3} for an unloaded ship,
C_f = 0.14 10^{-3} for loaded and unloaded ships.

Because the return current velocity and the water-level depression are functions of V_s, this speed cannot be derived straightforwardly. Given the propulsion power and the efficiency factor, it has to be determined through an iterative procedure using Schijf's method, for instance. Test results (Van de Kaa, 1978) showed that for a given value of the energy power the computed speeds of push-tow units deviated less than 10% from the measured ones. Only for channel widths that were small relative to the ship length deviations increased rapidly.

Ship speed

Computations with the equations above finally result in maximum ship speed attainable with the installed engine power. The computed speed should be less than the limit speed, as presented earlier in this chapter and summarised below.

According to the Schijf method, the limit speed in a width- and depth-limited channel follows from (see Equation 4.9):

$$\frac{V_{lim}}{\sqrt{g\bar{h}}} = \left[\frac{2}{3}\left(1 - \frac{A_s}{A_c} + \frac{1}{2}\frac{V_{lim}^2}{g\bar{h}}\right)\right]^{\frac{3}{2}} \tag{4.87}$$

In a waterway that is only depth-limited the limit speed follows from (combine Equation 4.29 and Equation 4.31):

$$V_{lim} = \sqrt{\frac{gL_s}{2\pi}\tanh\left(\frac{2\pi h_0}{L_s}\right)} \tag{4.88}$$

At open sea or very wide and deep waterways the limit speed reads (see Equation 4.29)

$$V_{lim} = \sqrt{\frac{g}{2\pi}L_s} \tag{4.89}$$

The limit speed according to Equation 4.89 is often called the hull speed. With g = 9.81 m2/s this becomes:

$V_{lim} = 1.25\sqrt{L_s}$ in m/s, or $V_{lim} = 4.5\sqrt{L_s}$ in km/hr, or $V_{lim} = 2.43\sqrt{L_s}$ in knots.

These limit speeds are applicable to water-displacement ships only. This type of ships cannot pass the Froude limit 1. Fast ferries or fast yachts can, because they can plane. The Ocean Race yachts, for instance, have a length of 19.85 m, which means that their top speed (speed over water) according to Equation 4.89 is about 20 km/hr. Yet, during the race in 2019 one of the yachts sailed 600 miles in in 24 hours, which is an average speed 45 km/hr (speed over ground). This difference is not likely to be explained by a strong following ocean current.

Equation 4.89 can also be rewritten in terms of a Froude number based on the ship length, a quantity often used in marine engineering:

$$Fr_L = \frac{V_s}{\sqrt{gL_s}} \tag{4.90}$$

This yields a limit Froude number of $1/\sqrt{2\pi} = 0.4$.

Figure 4.47 shows the relation between the limit Froude number and the ratio h_0/L_s for various values of the blockage factor. The deep-water limit value of 0.4 can clearly be seen for small values of A_s/A_c .

Generally, ships sail at about 70 to 85% of the limit speed, as above these values the wave or pressure resistance increases rapidly.

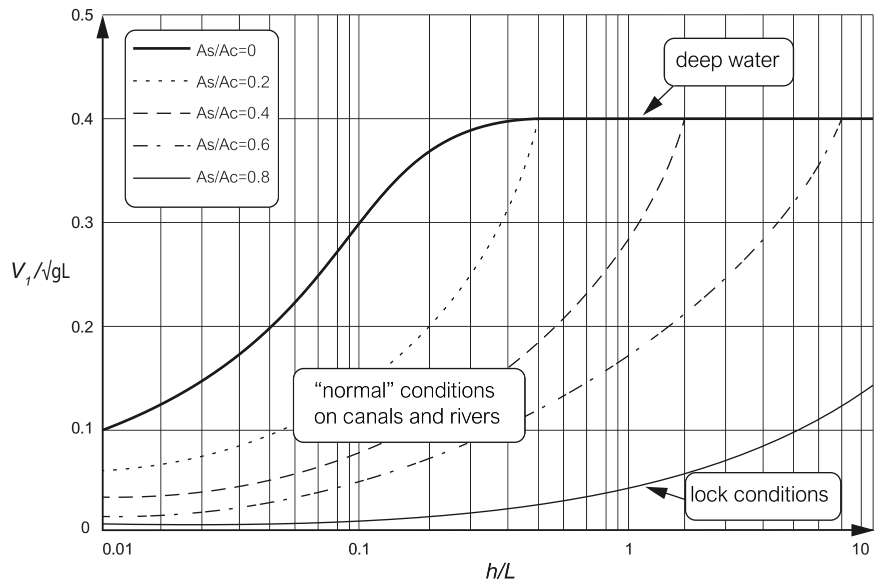


Figure 4.47: Relation between the limit Froude number and h_0/L_s (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

4.6 Numerical simulations

In the preceding sections we have presented analytical methods to describe the ship-induced water motion. Of course, it also possible to compute the ship-induced primary water motion with CFD models, using software systems such as Delft3D (Deltares), Mike software (DHI), FINEL2D (Svasek Hydraulics), or HIVEL2D (USACE-WES). These models are based on shallow water approximations (hydrostatic pressure distribution) and therefore describe the primary water motion. They are not suitable, however, to describe the secondary water motion. Figure 4.48 presents an example of a result of computations with FINEL2D. The ship is simulated by imposing a pressure distribution at the location of the ship, such that the water-level assumes the form of the underwater part of the ship. The picture shows the water-level depression and the flow field around the ship.

Figure 4.49 shows an example obtained with Delft3D of the flow velocities during an overtaking manoeuvre. Note the strong return currents, with velocities up to 2.5 m/s when the stern of the overtaking vessel is approaching

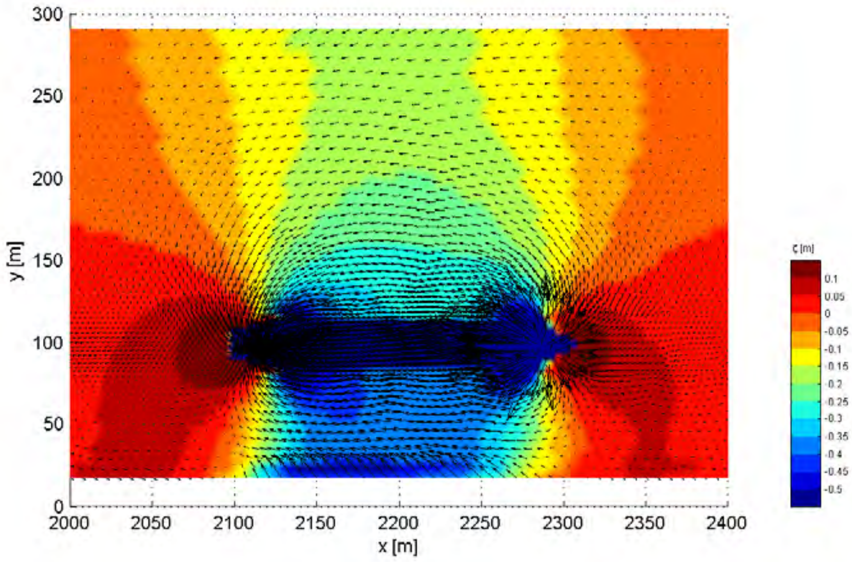


Figure 4.48: Water-level depression and velocity field around an eccentrically sailing ship (from red to blue: increasing water level depression). Image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0.

the bow of the overtaken vessel.

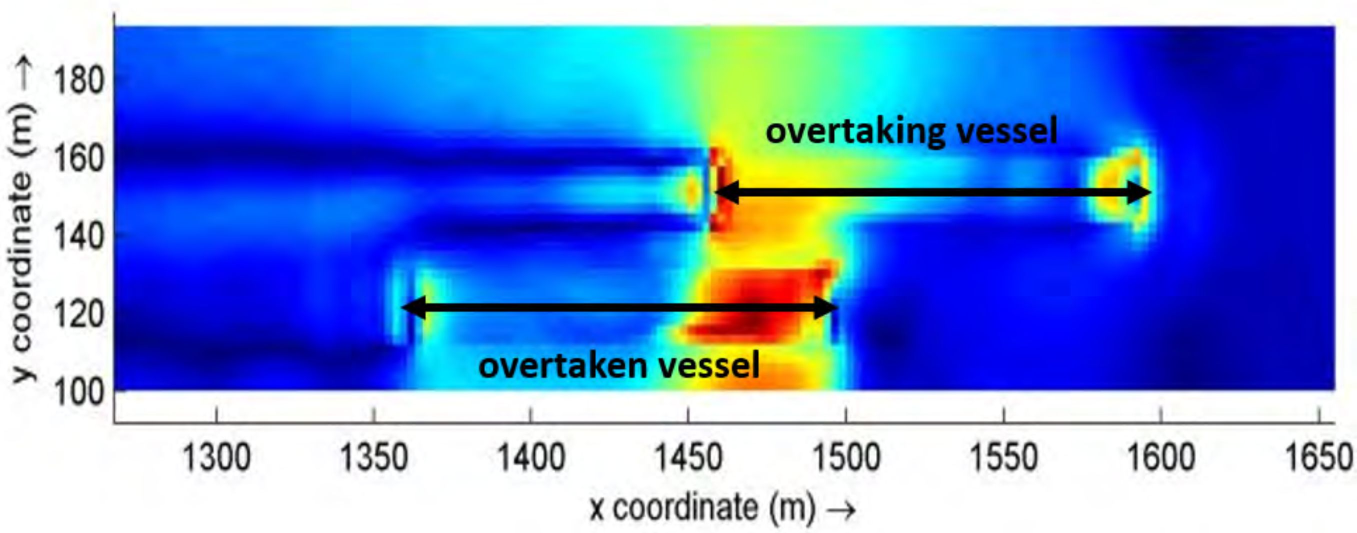


Figure 4.49: Simulation with Delft3D of two ships in an overtaking manoeuvre (image by Deltares is licenced under GNU General Public License).

Numerical simulation of the combined primary and secondary ship-induced water motion essentially includes simulation of wave generation and propagation, i.e. non-hydrostatic pressure. The Maritime Research Institute Netherlands (MARIN) has developed RAPID, a software system for the modelling of ship-induced wave generation, and Deltares has developed TRITON for wave propagation. Together these institutions initiated a study to investigate whether a combination of the two could do the job.

RAPID computes waves and currents induced by a sailing ship, thereby enabling variation in the modelling of aspects such as sailing speed, ship's dimensions and dimensions of the waterway. However, since RAPID was developed primarily to support ship design, it focuses on the near field, i.e. the area relatively close to the ship's hull. Consequently, RAPID does not include aspects such as refraction, diffraction and dissipation. Therefore, the results of RAPID have been used as input to TRITON. TRITON is based on the Boussinesq wave equations and has been developed to model propagation of shallow water waves, including features such as diffraction, refraction, wave-wave interaction and shoaling. Figure 4.50 shows the first result of the combined approach. They clearly show the primary and secondary water motion.

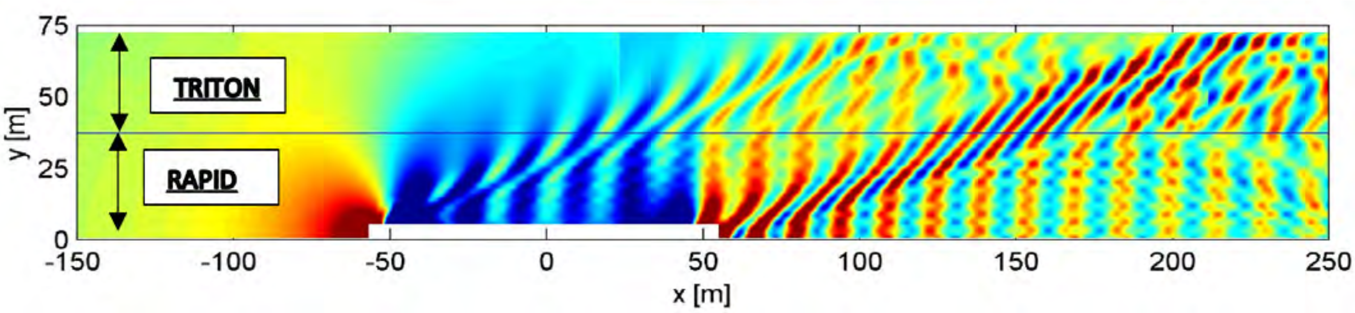


Figure 4.50: Ship-induced velocity pattern resulting from the combination of RAPID and TRITON (blue colours represent water level depressions and red colours water level elevations) (Verheij et al., 2001).

The effects of a sudden channel narrowing have also been simulated, for the situation around the Maeslandt Barrier in the access channel to Rotterdam. Figure 4.51 shows that high flow velocities occur, due to the high ship speed combined with the narrow cross-section and the presence of shallow areas near the bank.

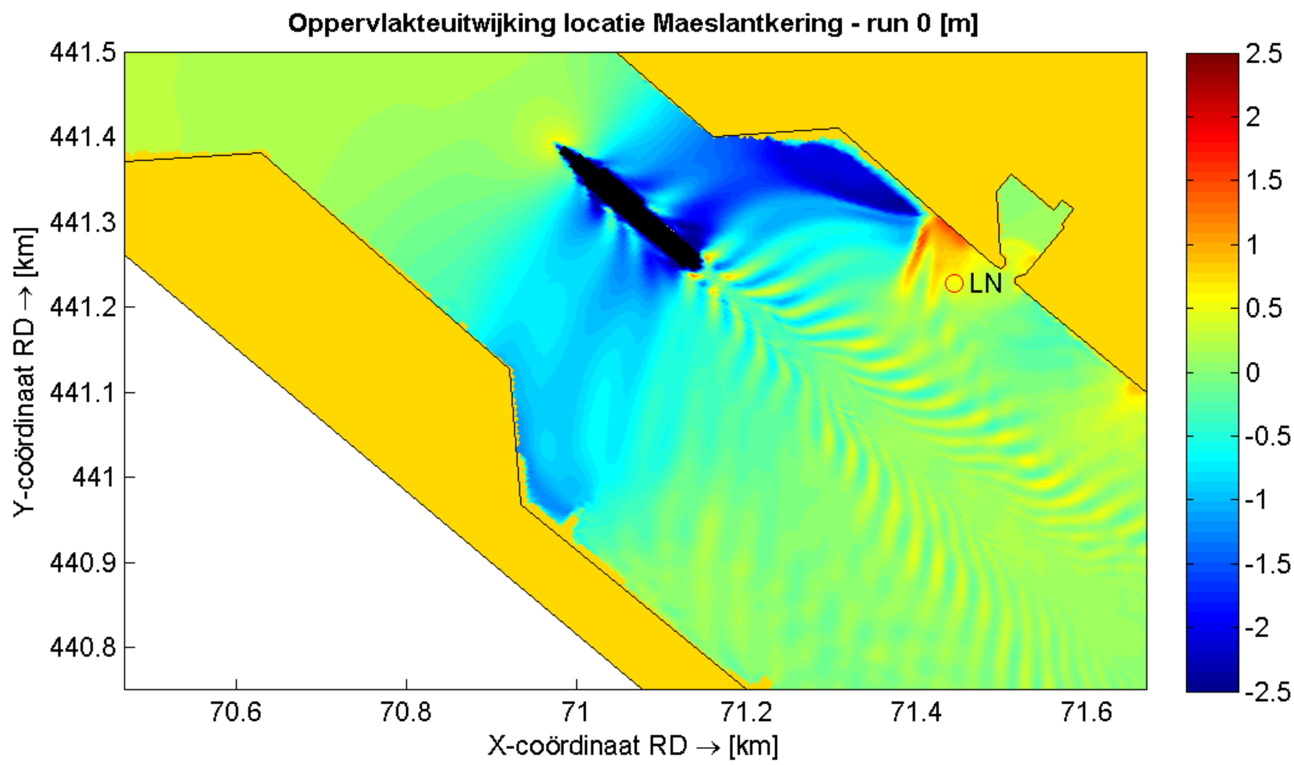


Figure 4.51: Flow field near the Maeslant barrier due to a ship passing a channel narrowing (Deltares, 2012).

Finally, we will show some examples of CFD results for flow velocities induced by propulsion systems. Figure 4.52 shows the flow field induced by a water jet directed towards the bed. Figure 4.53 shows the flow field in between a ship and the quay wall generated by a bow thruster.

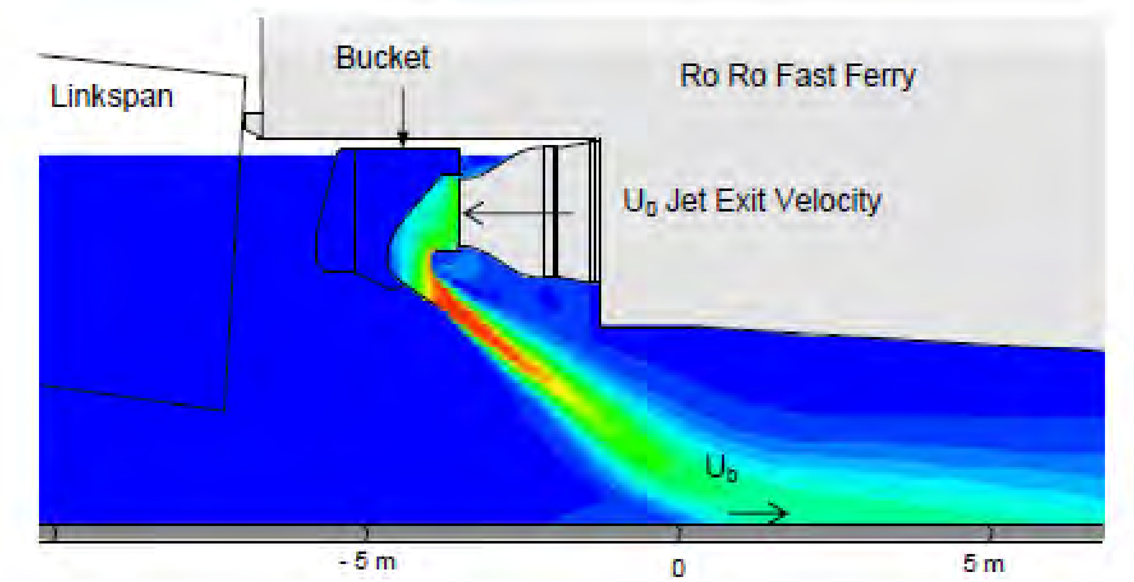


Figure 4.52: Flow field induced by a water jet (Hawkswood et al., 2013).

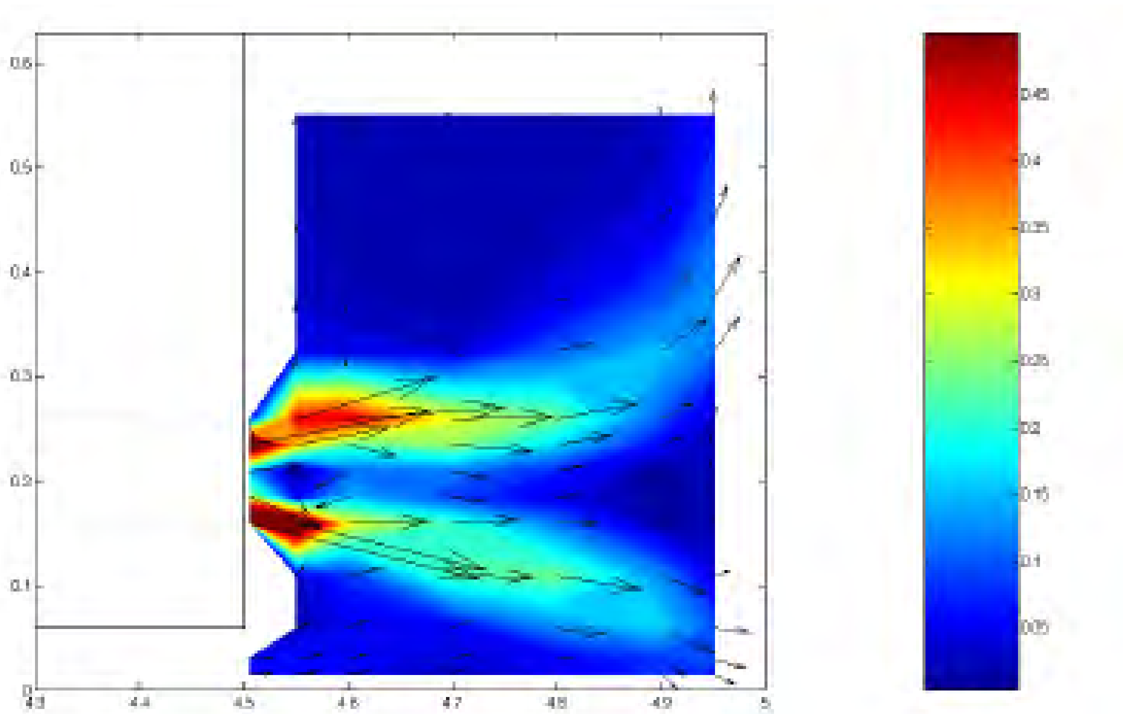


Figure 4.53: Flow field between ship and quay wall (Van Blaaderen, 2006).

5 Traffic management

Along with the increase of waterborne transport, the necessity of traffic management has increased, especially in coastal seas, harbour access areas and inland waterways. Whereas aboard the vessel, the captain was and is responsible for safe navigation, parties ashore have an interest in safe arrival and therefore provided aids to navigation. Management applies methods such as signalling, traffic separation, Fairways Information Services (FIS) and Vessel Traffic Services (VTSs). In this chapter we will give a brief summary of each of these methods.

5.1 Aids to navigation (buoys, beacons and traffic signs)

Signalling is the oldest means of traffic management. This first known lighthouse, for instance, the Pharos of Alexandria, Egypt, was built as early as 300 BCE and the oldest existing one, in La Coruña, Spain, dates from 20 BCE. Buoying systems have alo been in use for centuries. Until the seventies of the last century, over twenty different systems were in use worldwide, often conflicting with each other. It took a series of disasters to change this situation. In 1976 the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) came up with a uniform system (System A) that was agreed by the IMO. Introduced in 1977, its use has gradually spread throughout Europe, Australia, New Zealand, Africa, the Gulf and some Asian countries (together called Region A; see Figure 5.1). For the rest of the world (Region B, comprising the Americas, South-Korea and Japan; see Figure 5.1) the rules were completed in 1980.

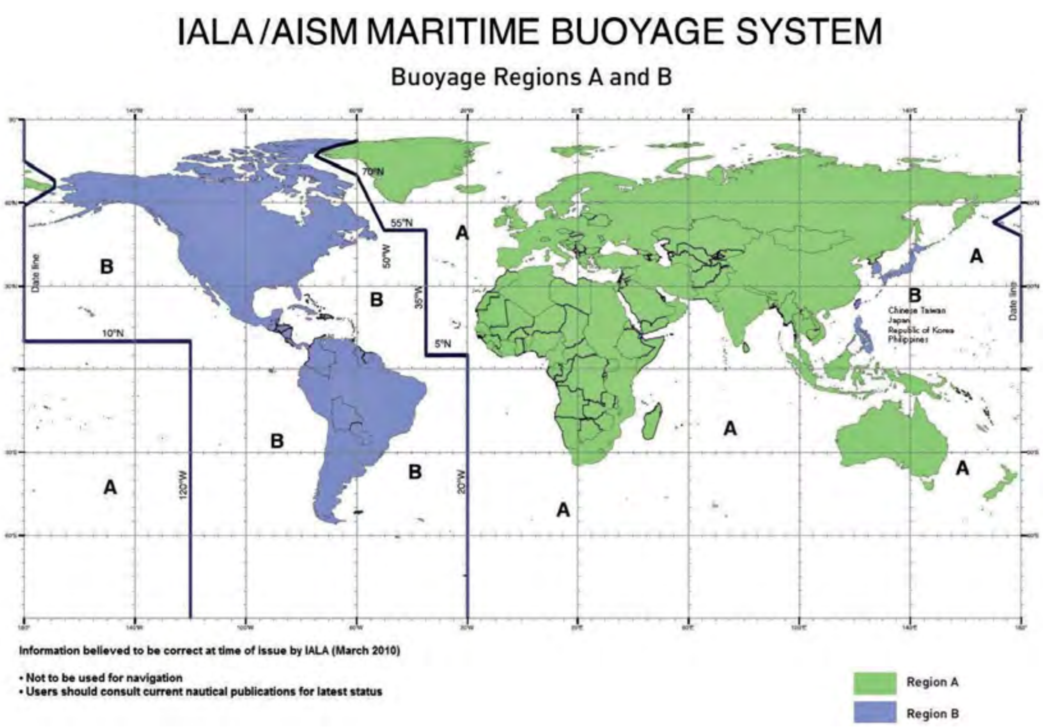


Figure 5.1: Worldwide distribution of buoyage systems. Image by IALA Navguide 2018 (reproduction for training or education purposes permitted, provided the attribution is mentioned).

The principal difference between the two systems are the lateral marks: red at port side and green at starboard side in Region A and conversely in Region B (see Figure 5.2). The other rules are so similar, that they have been laid down in 1980 in a single combined system, the IALA Maritime Buoyage System (MBS). In 2010, this system was extended by including other aids to navigation, to yield the IALA Marine Aids to Navigation System for fixed as well as floating devices (IALA, 2018).

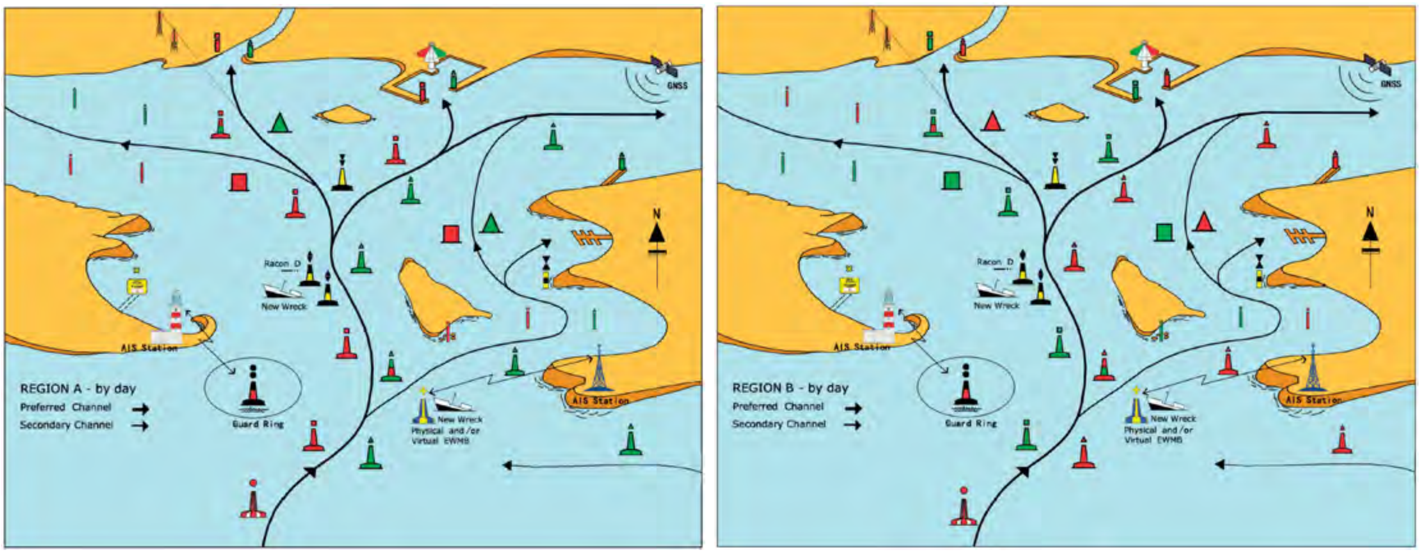


Figure 5.2: Worldwide distribution of buoyage systems, left: Region A, right: Region B. Image by IALA Navguide 2018 (reproduction for training or education purposes permitted, provided the attribution is mentioned).

The Marine Buoyage System encompasses six types of marks:

1. *lateral marks* – denoting the port and starboard sides of a navigation channel, each with a different colour (red or green, depending on the region, as described above); at bifurcations, a modified lateral mark may be used to indicate the preferred route designated by the competent authority; lateral marks are general numbered, with even numbers on the red buoys and odd numbers on the green ones; numbers increase in shoreward direction.
2. *cardinal marks* – indicating that the deepest water is at the named side of the mark; to that end, these marks have an agreed colour and flashlight code indicating whether this is the north, east, south or west side of the mark;
3. *isolated danger marks* – placed on, or near to a danger that has navigable water all around it; for the nature and extent of the danger, reference is made to nautical charts and publications; isolated dangers marks are clearly distinguished from cardinal marks by colour codes and flashlights;
4. *safe water marks* – have navigable water all around them without marking a danger; they may be used as fairway, mid-channel of landfall marks;
5. *special marks* – (always yellow) are used to indicate a special area or feature whose nature may be apparent from reference to a chart or other nautical publication; they are not generally intended for situations where the MBS provides suitable alternatives;
6. *new danger marks* – for newly discovered hazards that may not yet be shown in nautical documents and publications; until the information is sufciently promulgated, they should be indicated by using an Emergency Wreck Marking Buoy (EWMB), or deviating the traffic using appropriate means such as lateral, cardinal and isolated danger marks.

Apart from these marks meant to indicate navigable channels, there are marks meant to aid the mariner navigating, such as lighthouses, lightvessels, beacons, sector lights and leading lines, as well as port or harbour marks, such as breakwater lights, quay/jetty lights, traffic signals, bridge markings and inland waterways.

For further reading about the Maritime Buoyage System and the Marine Aids to Navigation System, we refer to the IALA Navguide 2018.

For inland waterways, the Economic Committee for Europe of the United Nations has issued the European Code for Navigation on Inland Waterways (CEVNI). Apart from sections on general conduct, rules and regulations, documents and onboard signs and signals, it gives and overview of waterway signs and markings, encompassing prohibitory, mandatory, restrictive, recommendatory and informative signs plus a number of auxiliary signs. Furthermore, it describes the buoyage of inland waterways, in line with the IALA Maritime Buoyage System.

In conformity with an earlier version of CEVNI, Rijkswaterstaat issued in 2008 the 'Richtlijnen Scheepvaarttekens', the Navigation Signs Directive (RST 2008), which apply to inland navigation in the Netherlands (Brolsma et al., 2008). They include chapters with specifications for traffic signs, light signals, Dynamic Route Information Panels (DRIPs) and fairway buoyage. Figure 5.3 gives a number of examples of traffic signs. At passings with a limited headway and a variable water level, such as fixed river bridges and bridges over tidal waters, skippers need to be informed of the actual headway. This is indicated by scales mounted on one or more bridge piers (Figure 5.4).

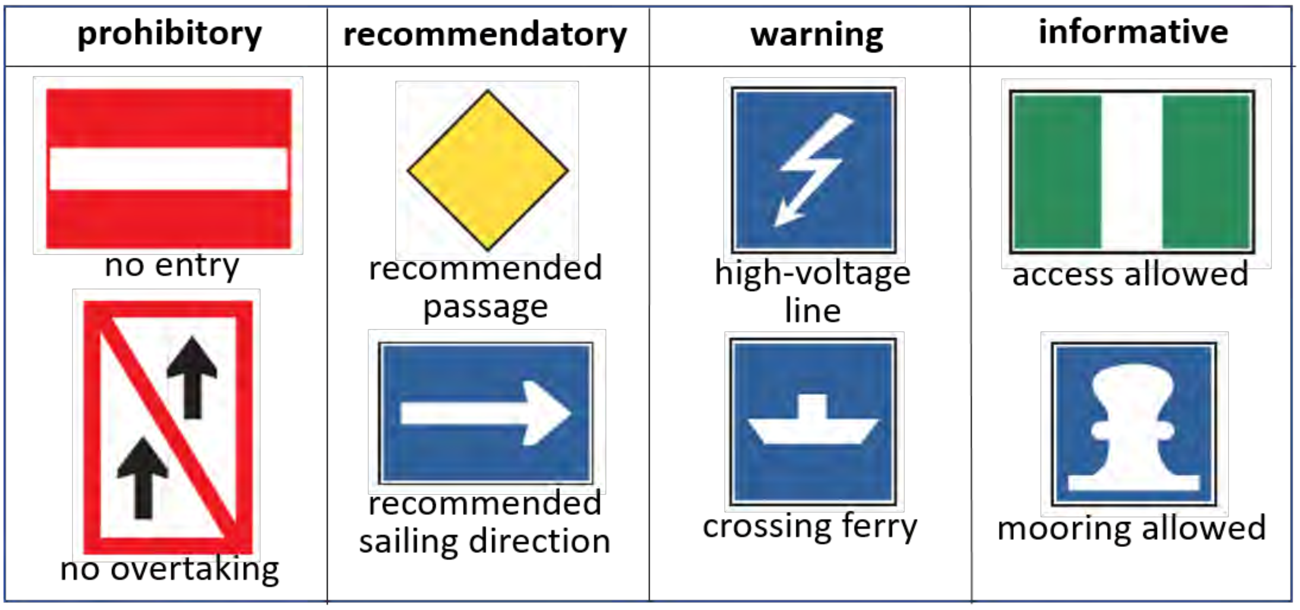


Figure 5.3: Examples of traffic signs for inland waterways (from Brolsma et al., 2008, Rijkswaterstaat).

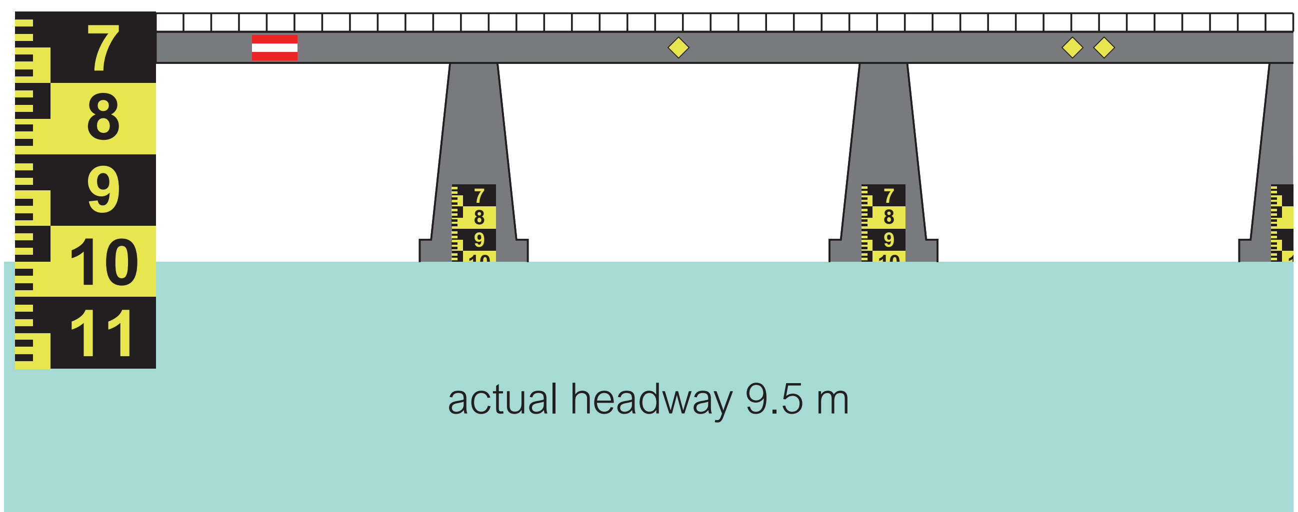


Figure 5.4: Use of scales to indicate the actual headway of a bridge (reworked from http://www.zeilvertrouwen.nl by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Fixed signal lights are used to arrange the passing of structures such as locks and movable bridges:

- two red lights indicate that the structure is permanently blocked and no passing is possible;
- a single red light indicates that the lock or bridge is in operation, but passing is not allowed now;
- a red-green light indicates that passing is about to be allowed;
- one green light means that passing is allowed;
- two green lights mean that passing is allowed and that the bridge is unattended, or the lock is open at either side.

Lights are also used to guide traffic in darkness. Figure 5.5 gives a schematic of how to illuminate a bridge passage. DRIPs give information referring to the actual situation on the waterway. Figure 5.6 shows an example.

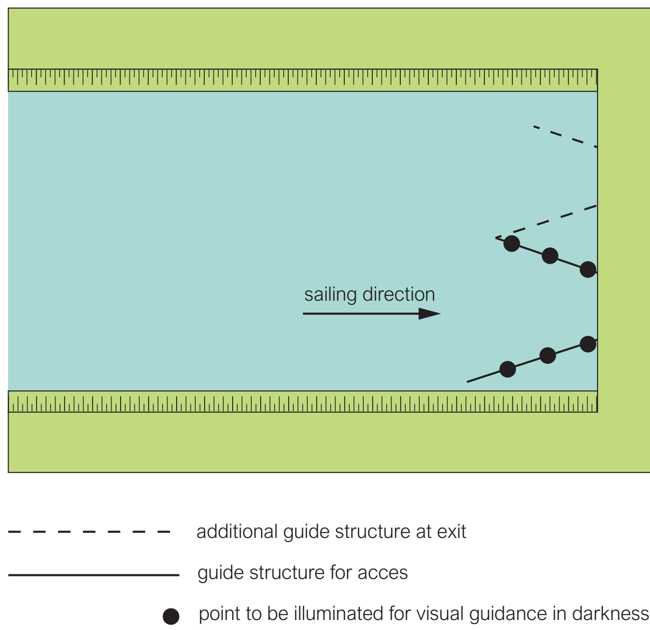


Figure 5.5: Illumination of a bridge passage (reworked from Brolsma et al., 2008, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 5.6: Example of a DRIP, saying: 'Bridge closes' (image from Rijkswaterstaat).

Fairway buoyage on inland waterways is quite similar to that at sea, except that that the numbering of the buoys runs seawards from inland. In tidal waters the numbers increase in the direction of the ebb current, in harbours they increase from sea to land. In the Dutch Western Scheldt, however, the IALA system is used. Left and right are always defined looking in the direction where the numbers increase.

In the SIGNI/CEVNI system for inland waters, red buoys and lights are on the right side of the fairway and green ones on the left side. Figure 5.7 gives an schematic of buoyance in a river section.

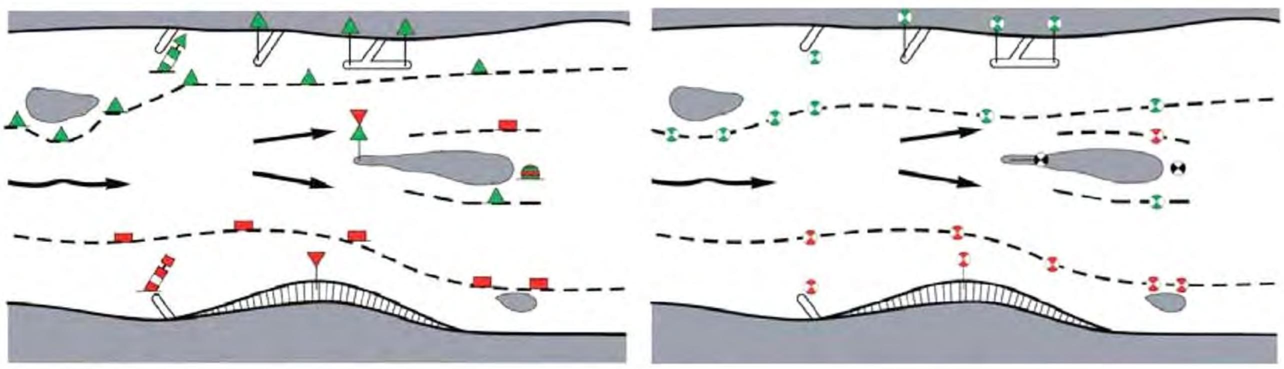


Figure 5.7: Schematic of SIGNI/CEVNI buoyance in a river (from Brolsma et al., 2008, Rijkswaterstaat).

For further details of inland waterway marks and signals, we refer to the latest revision of the CEVNI-code Inland Waterways.

5.2 Traffic Separation Schemes (TSS)

In order to improve safety in heavily navigated or congested seas, confined waterways and around capes, the IMO has introduced marine route systems (IMO Routeing Schemes) separating opposing traffic flows. The objectives of these schemes are:

- to help reduce and manage head-on situations for opposing traffic streams,
- to facilitate the safe crossing of traffic in the vicinity of a port,
- to keep traffic at a safe distance from facilities for offshore activities,
- to provide safe routes for deep-draught vessels,
- to avoid traffic in areas designated by the competent administration, and
- to better manage inshore traffic zones, fishing zones and areas with isolated dangers or shoal patches dangerous to navigation.

These Traffic Separation Schemes (TSS) designate traffic lanes, such that ships navigating in a lane all travel in the same direction, or they cross the lane at an angle as close to 90° as possible. In order to make this work, there must also be separation zones where no traffic is allowed and roundabouts where traffic flows can safely cross. Furthermore, a TSS may include precautionary areas, where navigation requires particular caution, and areas to be avoided by all ships. TSS rules are incorporated in the International Regulations for Preventing Collisions at Sea (COLREG). Figure 5.8 shows an example of a TSS.

The North Sea is not only heavily navigated, but also used for so many other purposes (e.g. hydrocarbon mining, windparks, nature reserves, fisheries), that a certain degree of spatial planning is needed (see, for instance, the North Sea 2050 Spatial Agenda of the Netherlands Ministry of Infrastructure and the Environment). In the North Sea, a distinction is made between route-bound and non-route bound shipping. The latter category includes short-sea, Ro-Ro ferries, work boats, fishing vessels and yachts that are all allowed to sail outside the TSS. The TSS implemented in the North Sea (see Part I –Figure 1.7) is therefore not only meant to make traffic safer, but also to confine it to certain zones.

Traffic separation by designated lanes is not common in inland waterways. Instead, traffic rules, regulations from police or waterway authorities, aids to navigation (also see Section 5.1) and Vessel Traffic Services (see Section 5.4) are the principal tools for traffic regulation. In general vessels pass each other at portside of the vessel, but this is not always possible. In river bends, for instance, deep-draught vessels may have to take the outer bend and pass at starboard-side of the encountering vessel, because the inner bend is too shallow.

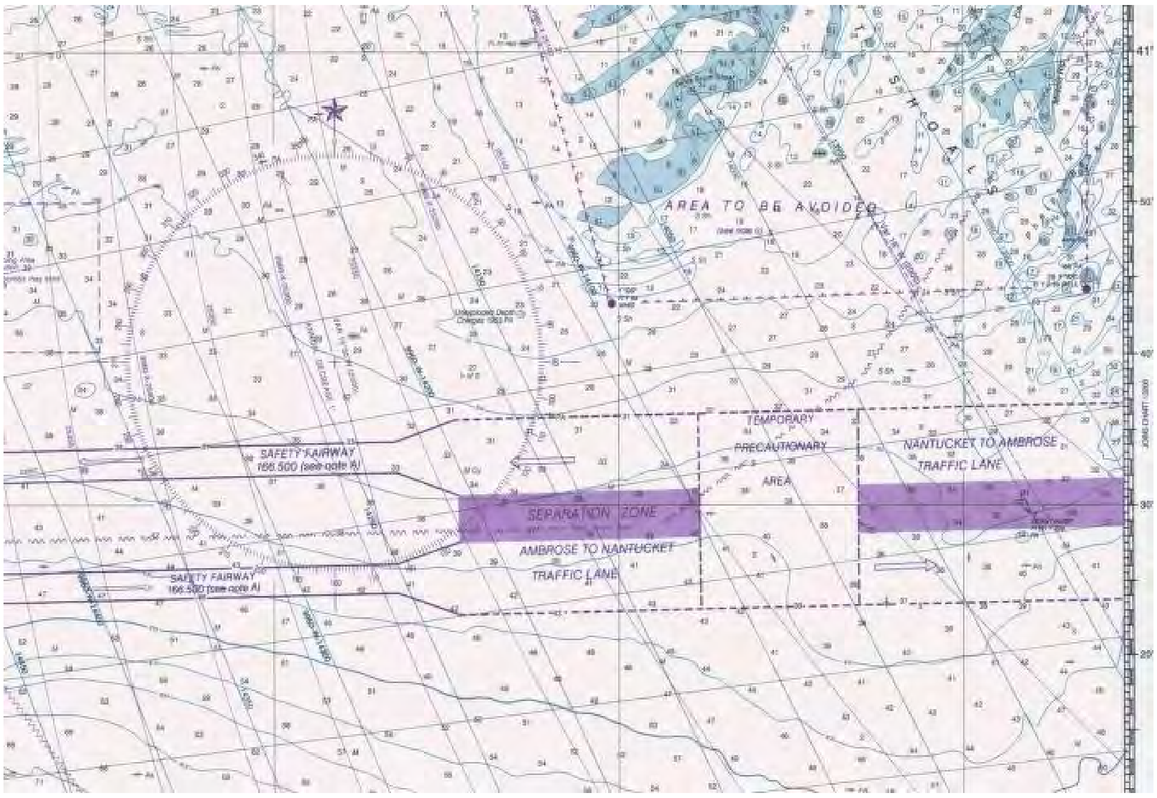


Figure 5.8: Example of a TSS (Chart1 by Wikimedia commons is licenced under CC0 1.0).

5.3 Fairway Information Systems (FIS)

River Information Services (RIS) use information technology to support traffic and transport management in inland navigation, including interfaces with other modes of transport, so as to improve the safety, efficiency and sustainability of inland shipping.

In 2005 the European Parliament and council adopted the River Information Services Directive (DIRECTIVE 2005/44/EC). It encompasses policy development, a legal framework, research and development and implementation monitoring. The Directive requires members states to implement RIS according to certain standards, referring to four key technologies:

- Inland Electronic Chart Display and Information System (Inland ECDIS),
- Notices to Skippers (NtS),
- Automatic Identification System (Inland AIS), based on transponder technology, and
- Electronic Reporting International (ERI).

Technical and operational standards for each of these technologies are defined and continuously updated.

The aims of this standardisation and harmonisation among EU countries are:

- to enhance safety in inland ports and on inland waterways,
- to protect the environment by providing traffic and transport information for effective calamity abatement,
- to enhance the efficiency of inland shipping by enabling information exchange between vessels, locks, bridges, terminal and ports,
- to use inland waterways better and more effectively by providing information on the status of the fairways,
- to enhance the efficiency of the entire multimodal supply chain by providing accurate and timely transport management information, and
- to enhance fuel economy through more accurate travel plans, so as to reduce greenhouse gas emissions.

In the Netherlands, Rijkswaterstaat implemented in 2011 the Fairways Information Services (FIS), in line with the RIS Directive. Via the website https://www.vaarweginformatie.nl it provides the following types of information in Dutch, English, German and French:

- notices to skippers,
- information such as service times and dimensions of bridges and locks, navigable depth of fairways, etc.
- water levels, discharges, headways, etc.
- seasonal information such as ice maps and swimming water quality, and
- electronic charts.

The site also offers downloads, such as a user manual and an overview of all public fairways in the Netherlands.

5.4 Vessel Traffic Services (VTS)

Already in 1968 the IMO issued VTS-guidelines, describing the function, set-up and operation of VTS in coastal waters, access channels and ports. The current version can be found in IMO-resolution A.857 of November 1997.

The IMO gives the following definition:

"Vessel Traffic Services – VTS – are shore-side systems which range from the provision of simple information messages to ships, such as position of other traffic or other traffic or meteorological warnings, to extensive management of traffic within a port or waterway."

Starting from the IMO guidelines, the CCNR has developed the Inland-VTS Guidelines, which are applicable to the waters under the Mannheim Act. As a member of both organisations, the Netherlands shall incorporate this in its legislation, in this case the Scheepvaart-verkeerswet (Vessel Traffic Act).

VTS systems are meant to improve the safety of navigation and the efficiency of vessel traffic, to protect adjacent communities, infrastructure and the environment, and to support security and law enforcement. They include facilities to interact with traffic participants in the area covered, who report to the authorities in charge.

The principal operational means to achieve this are:

- traffic supervision, aiming at safe and smooth traffic handling by means of personnel and infrastructural facilities,
- information on the status of the fairway,
- tactical information on the actual traffic, enabling immediate navigation decisions,
- traffic directions, binding orders meant to achieve or forbid certain traffic behaviour; a traffic participant must therefore always follow the directions given by a traffic supervisor (who then implicitly assumes the responsibility).

VTS aims at prevention as well as recovery. Traffic supervision is preventive, in that it aims at preventing accidents. This means that VTS operators have to monitor the traffic situation in real time, have to guard agreements for passing between vessels, and have to inform individual traffic participants on the traffic situation. The recovery function of a VTS primarily aims at limiting the consequences of accidents or incidents. This means that, once an accident occurs, the VTS makes an immediate analysis, in order to adequately alert the emergency services. It also informs the other vessels in the vicinity of the traffic and safety problems the accident entails. Furthermore, the VTS should ensure an orderly continuation of the traffic. Apart from this, a VTS can have several additional functions, such as providing lock and harbour information and gathering traffic data.

5.4.1 History

The development of radar technology during World War II offered great new possibilities for monitoring and tracking guidance for navigation traffic. In 1948, the first radar-based surveillance system was established in Liverpool, UK. In 1950, the USA followed with a system in Long Beach, California.

The first real 'traffic post' in the Netherlands was established at Brienenoord in 1966. In contrast to the 'bad weather posts' that existed up to that time, this one provided shipping with continuous radar information. In

1974 the post at Dordrecht was established, which grew into a fully-fledged vessel traffic service in the eighties (Figure 5.9). Since then the network of VTS posts in the Netherlands has been extended to the system shown in Figure 5.10.

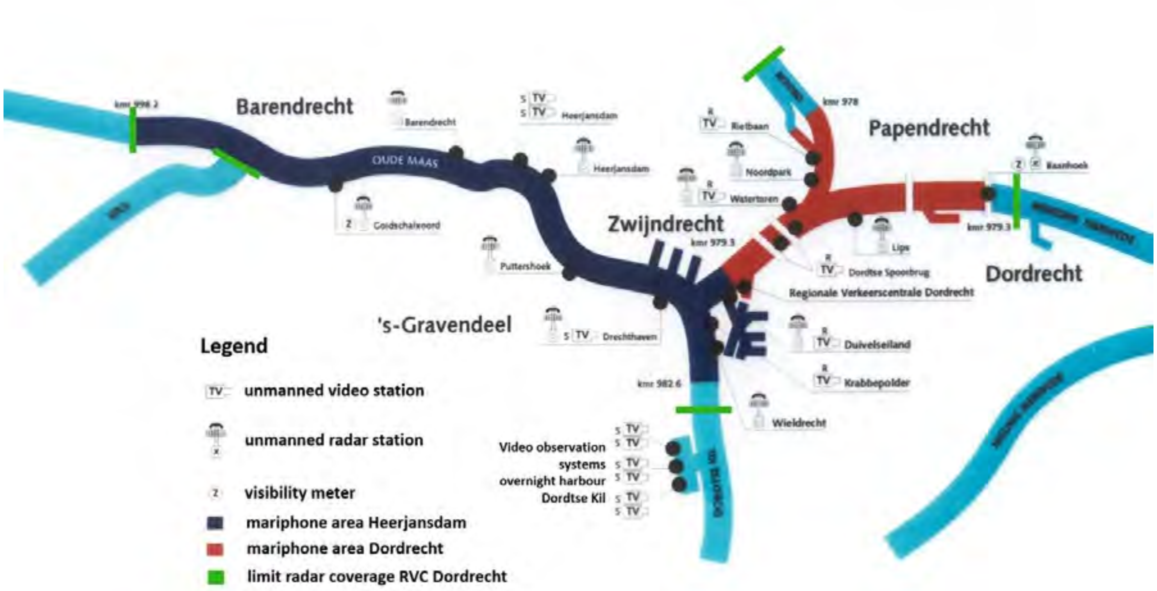


Figure 5.9: VTS-sectors area Regional Traffic Centre (RVS) Dordrecht (image from Rijkswaterstaat).

Figure 5.10: VTS-covered fairways in the Netherlands (image from RWS, 2016b, Rijkswaterstaat).

The authorities operate proactively in striving to remedy traffic bottlenecks on waterways. Initially there were more or less continuous proactive patrols by vessels, but the implementation of shore-based traffic posts has made clear that this preventative task can be carried out more cost-effectively from the shore (Figure 5.11).

Figure 5.11: Shore-based traffic supervision; left: traffic post Tiel (VTS monitoring post Tiel by melot001 is licenced under CC BY-SA); right: traffic supervisor (beeldbank.rws.nl, Rijkswaterstaat).

5.4.2 Analysis of the Netherlands' inland waterway transport

The Dutch government has been engaged in analysing the flow of waterborne traffic and transport for many years. Using information and tracing systems, it has attempted to find answers to questions such as: *How is the inland waterway network utilised?* and *Where do what types of ships operate and with what loads and draughts?* Such information enables early identification of bottlenecks and timely measures to avoid them.

In 1994 the 'IVS90' information system was put into operation. This system covered 80% of the Netherlands' main inland waterway network. In 2019 the system was replaced by the technically more advanced and more internationally oriented 'IVS Next', but the Informatie- en Volgsysteem voor de Scheepvaart (IVS) data are still being used for analysis. Ships report in with a set number of data when entering the IVS area and are followed during their journey. Rijkswaterstaat officers at locks and traffic posts also collect IVS data and have access to AIS data. Anonymised IVS- and AIS data are an important source for study and analysis.

This has resulted in a considerable amount of data on waterborne traffic and transport in the Netherlands. This information is used for statistical analysis, e.g. of all journeys in a certain time span, or the traffic intensity in a certain part of the network.

5.5 Safety

The number of accidents in inland transport is very small compared with the number of shipping movements. In total on average about 3000 accidents occur yearly of which about 1000 are registered (RWS, 2016a). Of the registered accidents about 150 are serious accidents with victims/casualties and/or serious damage. These figures have remained more or less constant over the past years. Therefore, the main task of the traffic posts is shifting from supervising and directing traffic to providing skippers and barge captains with information, for instance on the situation at the next lock. Thus the vessel speed can be adjusted, so as to reach the lock at the right moment and to optimise fuel consumption.

The traffic posts are in operation 24/7, with only a few people working in each post. In order to promote safety, traffic post personnel is instructed to be brief, professional and precise in VHF communication, with testing and re-examination of procedures every three years.

Interaction with recreational craft

The number of recreational yachts in the Netherlands is a multiple of the number of commercial vessels. The interaction of barge traffic with recreational cruising is therefore an important issue, requiring special safety measures. Vessels are not obliged to give a call when entering a VTS domain, only if a dangerous situation might occur, for instance if the vessel does not sail at the starboard side of the waterway. Yet, this does not always work in practice, especially not for recreational craft. For the sake of safety, the post nevertheless can provide other traffic participants with details of recreational craft positions on the waterway as far as identified. Also, in order to be understandable to lay people, officers at the post are specially trained to avoid professional jargon in such situations.

Part IV

System performance

1 Performance of ports and waterways

1.1 System performance

Supply chains and the enabling transport systems are dynamic systems, with complex interactions between components and behaviour that cannot always be explained by the behaviour of the individual components. Consequently, the performance of such systems is not simply the sum of the performances of its elements.

Despite this complexity, quantification of performance, in whatever terms, is crucial to the continuous improvement of supply chains. The success of this process determines the transport costs for the client, as well as the choice of shippers for the mode and corridor of transport. Thus, it determines the competitive edge of all actors in the chain. It is clear that a good overview of how the system elements interact and the system functions is key to this success.

More in general, Part II and Part III of this book have dealt with the design, operations and management of the elements of a transport system, namely ports, port terminals, and waterways. Part IV concerns their joint functioning in the transport system as a whole. It defines system performance, describes how one can quantify it and investigates a number of phenomena influencing it.

We illustrate this by the example of port adaptation to hydrogen transport (Figure 1.1; also see Lanphen, 2019). Hydrogen is expected to become an important carrier of clean and renewable energy and port authorities are already considering what role they wish to play in the hydrogen supply chain.

Figure 1.1: Artist impression of the world's first liquefied hydrogen carrier, the Suiso Frontier, (actually launched December 2019) (© Kawasaki Heavy Industries).

Hydrogen can be produced from different sources, among which fossil fuels and natural gas, but also water (via electrolysis). At the moment, production from natural gas is the most cost-effective. This may change if the by-product CO_2 has to be captured and stored, or if CO_2-prices are raised. Hydrogen can be stored and transported in different forms, called carriers (gaseous, liquefied, or chemically bound). Depending on the carrier and the location, long-distance transport can take place by ship or by pipeline.

Because of the low density and the low boiling point under atmospheric conditions, gaseous hydrogen has to be stored and transported under high pressure. Liquified hydrogen is stored and transported at a temperature of -253°C. Chemically bound hydrogen, e.g. in the form of ammonia (NH_3) or methylcyclohexane (MCH), can be stored and transported under less extreme conditions, but involves efficiency losses due to the chemical binding and retrieval processes.

Figure 1.2 gives a schematic overview of the hydrogen supply chain. It shows that many actors have to agreed about the choices to be made to ultimately bring the hydrogen from producer to distributer. Although there may be power differences, none of these actors can decide on their own; they are all interdependent. For the port authorities of the exporting and the importing port, for instance, it makes a lot of difference in which form the hydrogen is transported, with regard to the processing plant, terminal type (liquid or dry bulk), for the safety zones and for the facilities and the storage capacity at the terminal. They cannot independently optimise these investments and their timing, however; the plans and interests of the other parties involved have to be taken into account. This requires not only a good overview of what, where, when, who and how in the supply chain, but also a certain degree of coordination and collaboration.

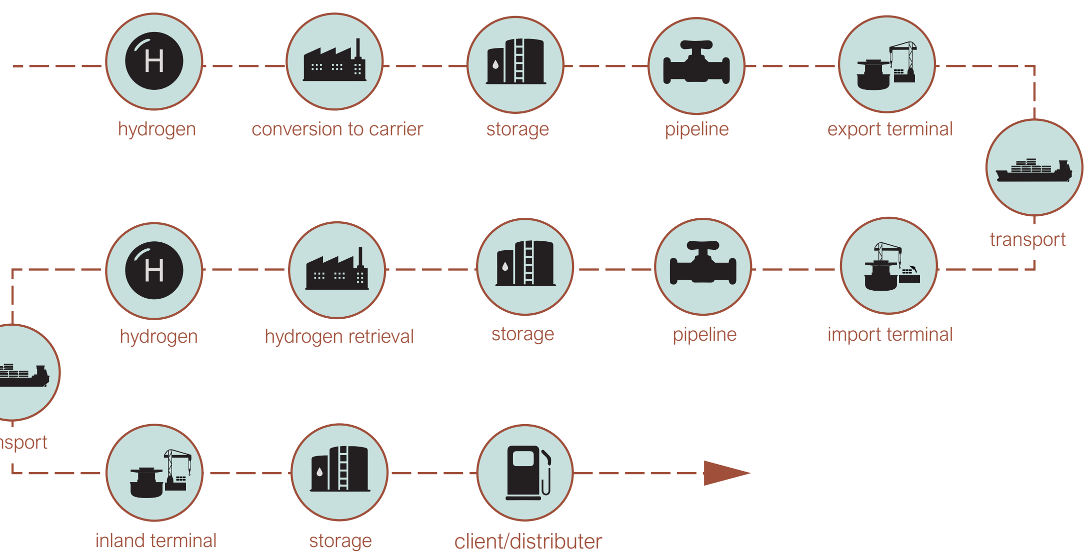


Figure 1.2: Schematic of a hydrogen supply chain (modified from Lanphen, 2019, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

1.2 Design and performance evaluation

Performance is a vague notion as long as it has not been expressed in more specific identifiers and there are no clear overall objectives. For a supply chain common objectives are:

- cost-effective operation,
- sufficient throughput,
- sufficient capacity of all elements in the chain,
- timely delivery,
- safety (i.e. acceptable risk),
- environmental friendliness, and
- security.

De Vries et al. (2021a,b) identified this need to 'objectify' performance concepts. With objectification they mean turning the implicit into an explicit engineerable 'object', on the one hand, and specifying clear design 'objectives', on the other. They propose using the Frame of Reference (FoR) as a method to systematically transform 'vague' performance concepts into functionally specified engineering designs.

Objectives, in the sense of the FoR approach (Part I – Section 2.2.2), are typically formulated in normative terms, i.e. 'cost-effective', 'sufficient', 'timely', 'acceptable', etc. In order to be suitable for optimisation, they need to be expressed in terms of quantifiable parameters (in FoR-terms: Quantitative State Concepts (QSCs)) that can be used to develop indicators, viz. assemblages of QSCs that indicate whether or not there is a problem (comparing an observed or estimated state with a desired state).

Quantification considerations

The quantification method and Quantitative State Concepts (QSCs) to be used, as well as the required level of detail and accuracy, depend on the situation.

In the concept design phase, it is typically important to narrow down to a few options from a broad range of alternatives. Since the main goal is to 'rank and filter', often in a context of still-changing demands by the client, it is generally sufficient to estimate order-of-magnitude dimensions per alternative, and determine how sensitive these alternatives are to changing boundary conditions. Accuracy is important to the extent that the ranking should be trustworthy, but insufficient time, resources and information are available to elaborate each alternative to the last nut, bolt and Euro. Performance metrics are estimated by rules of thumb or determined with more rigorous parametric calculation methods, though often with coarse estimated inputs.

In the detailed design phase it is important to demonstrate that a design satisfies a number of criteria, imposed by the client, by law and/or by the environment (i.e. safety, stability, baring capacity, operability, robustness). Since the main goal of this phase is to 'select and implement', the required accuracy is much higher, since design flaws can lead to significant cost overruns and severe damages. Performance metrics in this case follow from detailed engineering studies, that are driven by high-quality inputs derived from site surveys, detailed measurements and advanced models and simulations, and may take months to years to complete.

In the operational phase, performance metrics can be measured directly or estimated with operational models that predict winds, currents, waves and subsequent impacts on operations on a daily basis. When the aim is to enable timely (and often costly) intervention in operations, i.e. temporary suspension of operations due to imminent weather conditions, it is important that performance metrics and associated intervention triggers are accurate and trustworthy.

From the above-mentioned issues a few general considerations regarding quantification emerge:

- *Accuracy* – especially in the concept design phase inputs are generally based on estimates (e.g. demand, vessel mix, (un)loading rates, discount rate), and models used are typically schematic representations of reality (e.g. Schijf's model of water level drawdown described in Part III – Section 4.1, or the queuing models described in Section 2.4). But even in the detailed design and operational phase not everything can be measured exactly, so for the assessment of some metrics one needs to use estimates or models. It is important to carefully consider the appropriate level of accuracy of quantifications.
- *Variability* – performance metrics may be variable at different temporal and spatial scales, so a snapshot or local observation may not be representative. Designing for a pre-defined operability level requires sufficiently long time series of waves and water levels. Currents that influence port accessibility will vary with tides, day-to-day weather conditions and port configuration, which generally requires point measurements to be combined with models to arrive at synoptic information. It is important to consider the types of variability that may affect decision making and incorporate these in the QSC.
- *Interpretation of measurements and trends* – due to the complexity of port and waterway systems, changes in local performance metrics are not always easily translated to performance metrics at system scale; cause-effect relationships may be intricate and adequate countermeasures may not be obvious: Prolonged droughts may lead to lower water levels. Reduced loading rates, to avoid grounding, may lead to an increased number of trips to move the same amount of cargo. As a result, a depth-bottleneck on an inland waterway, may lead to increased traffic and congestion in a seaport several hundreds of kilometres downstream. It is important to select the appropriate system boundaries and include the appropriate level of detail.

Understanding the functioning of the supply chain and its components is therefore a prerequisite of designing effective QSCs.

Performance indicators

As mentioned in Part I – Section 2.2.2 we define indicators as assemblages of QSCs that indicate whether or not there is a problem. A problem can be identified from comparing an observed or estimated state with a desired state. For port and waterway problems we typically look for indicators regarding supply chain performance. Examples are indicators for:

- *cost-effectiveness (depending on the actor's perspective)* – Net Present Value (NPV) of a terminal operation, cost per ton hydrogen, cost per Twenty Feet Equivalent Units (TEU), demurrage costs associated with vessel waiting times, etc.;
- *throughput* – number of TEU, cars or passengers handled per unit time, tons of dry or liquid bulk handled per unit time, etc.;
- *capacity* – maximum number of vessels that can pass per unit time through a waterway or a lock; maximum amount of cargo that can be handled per unit time at a port terminal, etc.;
- *timely delivery* – percentage of deliveries on time, average delay, waiting times as a factor of service time, etc.;
- *safety* – number of accidents as percentage of the number of operations or events (e.g. ship encounters), number of casualties relative to the number of personnel days, risk defined as probability of occurrence of an undesired event times the damage done, etc.;
- *environmental sustainability* – energy consumption, fossil fuel consumption, emissions (CO_2, SO_x, NO_x, PM-x etc.), production of turbidity, waste or pollutants, nature-inclusiveness of structures, etc.;
- *security* – value of stolen goods, costs of vandalism, amount of illegally imported goods.

To function as indicators each of the examples mentioned above requires a QSC for quantification and a reference value to determine whether or not the current or and estimated state is to be considered problematic. A set of indicators can be like a set of meters on a dashboard: they enable monitoring the system's performance and trigger corrective measures if necessary.

1.3 Performance analysis

When investigating the performance of a supply chain (sub)system, it is important to separate it from the adjacent systems, such that changes in its state don't interact with the states of the other systems. In space-time problems, this means that the system boundaries have to be chosen far enough away in space and time to avoid this interaction, such that the boundary conditions can be considered as a given. In a supply chain, the system components (nodes and branches) are connected, so one simply has to assume that this interaction does not take place. Once the (sub)system's separate performance has been determined, its interaction with the adjacent (sub)systems can be analysed.

Figure 1.3 outlines the general approach to performance analyses. The system component to be considered is separated from the adjacent ones by defining the 'boundary conditions' (bc), which are in fact the inputs from the adjacent components. In the case of a port, for instance, this can be the cargo flows shown in Figure 4.26 and Figure 4.27 in Part II – Chapter 4.

Once the objective of the analysis has been identified ('problem objectification'), it is useful to first formulate a verbal model. Such a model outlines in words how the system functions, in terms of determining factors and cause-effect relationships. It may be laid down in a 'mindmap', a flow diagram mapping out the relationships between the most important factors. This not only helps structuring the analysis, it is also an important aid in explaining the system to a lay audience.

Depending on the system's complexity and the accuracy requirements of the performance analysis, one may choose for quantification with empirical rules of thumb, an analytical model (generally a set of calculation rules, if necessary supported by tabulated information), or a numerical simulation model. In design processes, these methods are often used successively as the design proceeds. This is discussed in more detail in Chapter 2.

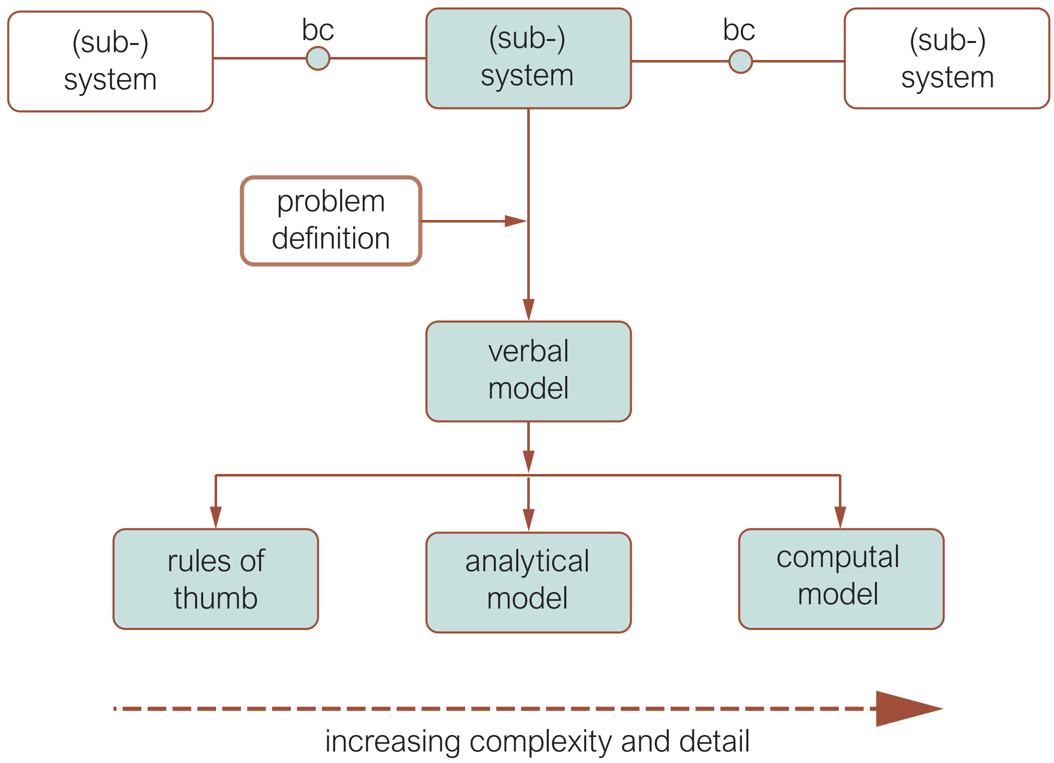


Figure 1.3: General approach to performance analysis (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

2 Performance quantification

2.1 Data acquisition and validation

[1]Data is needed to establish empirical relationships between parameters, but also to calibrate and validate models. The quantity and quality of those data has to be sufficient to achieve the accuracy required.

In order to gather the necessary data, one may go out and make one's own observations during some time. Rijkswaterstaat engineer Kooman, for instance, observed in the 1970's vessel passages and waiting times at various locks in the Netherlands. His observations are the basis of a number of empirical rules used in the so-called Kooman method to estimate waiting and passage times at locks (Kooman and De Bruijn, 1975).

Another approach is monitoring. This can be done at a specific location with equipment taking continuous measurements and transmitting or logging the data. But it can also be done by asking actors to collect and transfer data during their operations. The International Maritime Organization (IMO) requirement for ocean-going vessels to share their data on fuel oil consumption is one example, the request to Inland Water Transport (IWT) vessels to share their soundings for Covadem is another (also see Part I – Section 2.1.1).

This multi-source data acquisition may conflict with prevailing legislation about privacy or data ownership. Privacy problems can be avoided by anonymisation, but in many countries ownership is a more problematic issue, especially if data is traded against money, or if they are considered of strategic importance. Yet, it is important that data can be shared, if only because they are of more value together than in isolation.

When applied to similar situations, a well-validated model may produce results that correlate so well that they can be captured in a rule of thumb. In that case the model can be considered the data source.

Before being made available for further use, the data quality needs to be checked. Not all observations are equally accurate; sometimes values may lie far out side the normal distribution (outliers) or be obviously wrong. Such values need to be explained or removed from the set, otherwise they may lead to a false correlation. Figure 2.1 shows an extreme example, in this case for the value of imported agricultural goods in the EU.

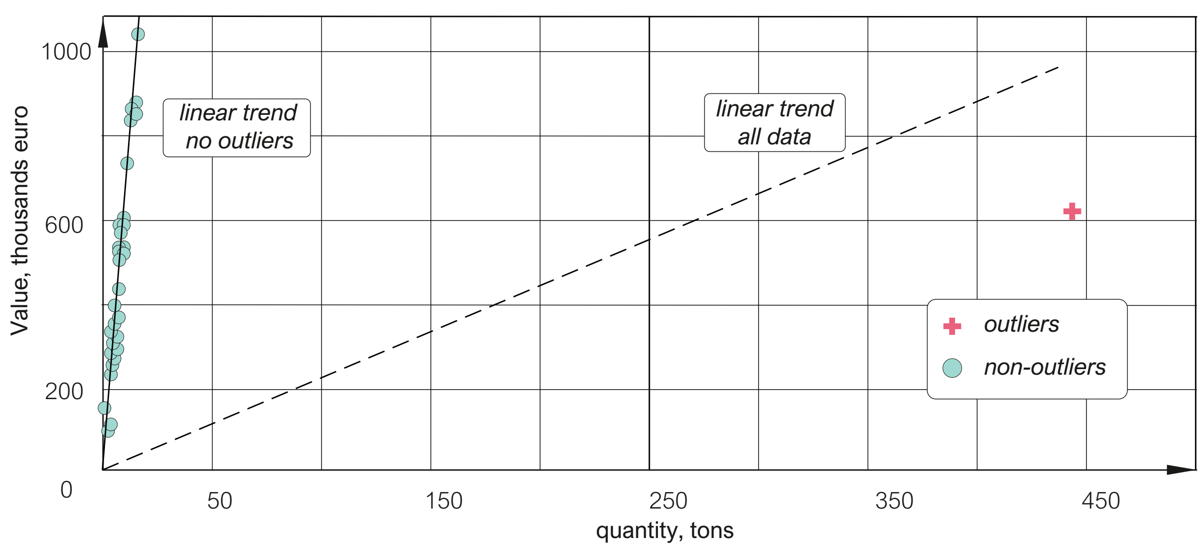


Figure 2.1: Outlier effect on the relationship between two parameters (reworked from Kopustinskas and Arsenis, 2012, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

[1]This chapter made use of '*Service systems in ports and inland waterways*' (Groenveld, 2001), lecture notes for the Ports and Waterways courses CIE4330 and CIE5306 at TU Delft.

2.2 Empirical rules

Empirical rules, or rules of thumb, are based on experience, observations or model results concerning the relationship between two or more parameters, like in Figure 2.1. In principle, their validity is restricted to the locations and time intervals in which the observations have been made, or to which the model has been applied. Extrapolation to other situations can become very inaccurate and therefore requires explicit validation.

The observations used are mostly measured or recorded data on the parameters to be correlated. As such data are usually scattered, statistical methods such as regression analysis are used to establish the relationship. Artificial Intelligence techniques can be used, also to derive more complex relationships from data. In any case, an accuracy measure, such as the correlation coefficient R or the coefficient of determination R^2, is a useful addition (see, for instance, Figure 2.2).

Rules of thumb are widely used in waterborne transport systems. Many dimension requirements regarding waterways or water bodies in ports (see Part II and Part III) are experience-based and therefore actually rules of thumb. They are also often used in (pre-)feasibility studies and in the early design phases of infrastructure. In the following sections we will give some performance-related examples.

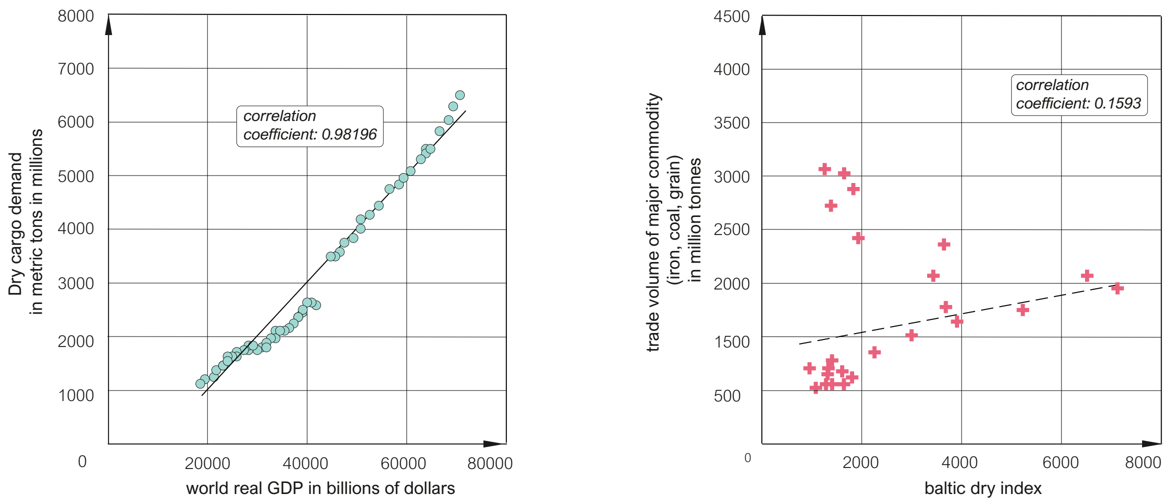


Figure 2.2: Relationships with different correlation coefficients (reworked from Akyar, 2018, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

2.2.1 Port performance

In Part II we have shown examples of terminal throughput and storage capacity calculations. If such calculations are too laborious, e.g. in a (pre-)feasibility study or an early design phase, one may use rules of thumb to gain a rough indication of what to expect.

One example is the capacity of a berth, which is of course proportional to its availability, its occupancy and the capacity of the equipment handling a ship. In a formula (also see Ligteringen, 2017):

$$C_b = PNn_dm_b \tag{2.1}$$

in which:

C_b	=	estimated berth capacity in ton/yr or TEU/yr,
P	=	(un)loading capacity per unit handling equipment in ton/hr or TEU/hr,
N	=	number of (un)loading units operating on a ship of average size,
n_d	=	berth availability = number of operational hours per year,
m_b	=	berth occupancy factor = fraction of the time that the berth is occupied.

The values to be substituted into Equation 2.1 are experience-based, which makes this a rule of thumb. Table 2.1 gives typical ranges of results, expressed in throughput capacity per unit quay length or per berth (in the case of a crude oil jetty).

Cargo type	Capacity range	Units
Conventional general cargo	500 – 1,000	ton/yr per m^1 quay length
Containers	800 – 1,700	TEU/yr per m^1 quay length
Coal import (Van Vianen et al., 2011)	10,000 – 30,000	ton/yr per m^1 quay length
Coal export (Van Vianen et al., 2011)	50,000 – 150,000	ton/yr per m^1 quay length
Iron ore import (Van Vianen et al., 2011)	25,000 – 75,000	ton/yr per m^1 quay length
Iron ore export (Van Vianen et al., 2011)	20,000 – 60,000	ton/yr per m^1 quay length
Crude oil (VLCC and ULCC)	70 million	ton/yr per berth

Table 2.1: Empirical capacity ranges for different types of cargo (Ligteringen, 2017).

One may also use rules of thumb to estimate the throughput capacity per unit storage area. Table 2.2 gives some ranges per cargo type. The storage area is the gross storage area and includes the net storage area and internal roads, pipelines and/or conveyor belts and equipment rails at the storage yard.

Cargo type	Capacity range	Units
Conventional general cargo	4 – 6	ton/yr per m^2 storage area
Containers (Drewry, 2010)	0.75 – 5.5	TEU/yr per m^2 storage area
Coal import (Van Vianen et al., 2011)	15 – 75	ton/yr per m^2 storage area
Coal export (Van Vianen et al., 2011)	30 – 200	ton/yr per m^2 storage area
Iron ore import (Van Vianen et al., 2011)	30 – 80	ton/yr per m^2 storage area
Iron ore export (Van Vianen et al., 2011)	60 – 200	ton/yr per m^2 storage area
Crude oil	40 – 50	ton/yr per m^2 storage area

Table 2.2: Empirical throughput capacity ranges per unit storage area (Ligteringen, 2017).

The total terminal area, in addition, includes the other buildings and infrastructure in between quay and yard on the terminal. For a first-order estimate of the total terminal area, the following rules of thumb can be used:

Cargo type	Total terminal area [m^2]
Containers	total quay length [m] * 400 – 500 m
Dry bulk (Kox, 2017)	gross storage area [m^2] * 1.4 – 1.5 m
Liquid bulk (Kox, 2017)	gross storage area [m^2] * 1.6 – 1.7 m

Table 2.3: Total terminal area estimation (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

In the example elaborated in Part II – Chapter 4, a first-order terminal design was made for a container terminal with straddle carriers and an annual throughput of 2,460,000 TEU. The estimated quay length of 1,579.7 m translates to 1,557 TEU/yr per m^1 quay length. The estimated storage area of 494,000 m^2 for just the stacks and 593,787 m^2 including roads, translate to 5.0 and 4.1 TEU/yr per m^2 storage area respectively. The apron area of

129,533 m^2 plus the storage area including roads, divided by the quay length translates to a terminal depth of 458 m. It may be observed that these values fall well within the ranges shown in Table 2.1 to Table 2.3.

A rule of thumb often used in port development refers to the (non-linear) relationship between berth occupancy and waiting time. As soon as the occupancy factor exceeds 0.5, waiting times increase rapidly. This means that the number of berths needs to be increased in order to keep waiting times within the agreed bounds. Building or extending quays, however, is a costly and lengthy procedure, which means that studies and design procedures have to start at lower values of the occupancy factor.

Apart from capacities and cost-benefit ratios, safety is an important quality identifier for ports. Safety may concern the risk due to a hazardous event in a port, such as an explosion at an Liquified Natural Gas (LNG) terminal (Figure 2.3). Here risk is defined as the probability of occurrence of the event, times the impact in terms of material damage (material risk) or casualties and injuries (personal risk). The risk level calculation is to a large extent empirical, if it were only because the impact of a hazard is experience-based. While the risk contours are determined using models, the empirical factors depend on the degree of overpressure, toxicity or temperature increase causing a hazard.

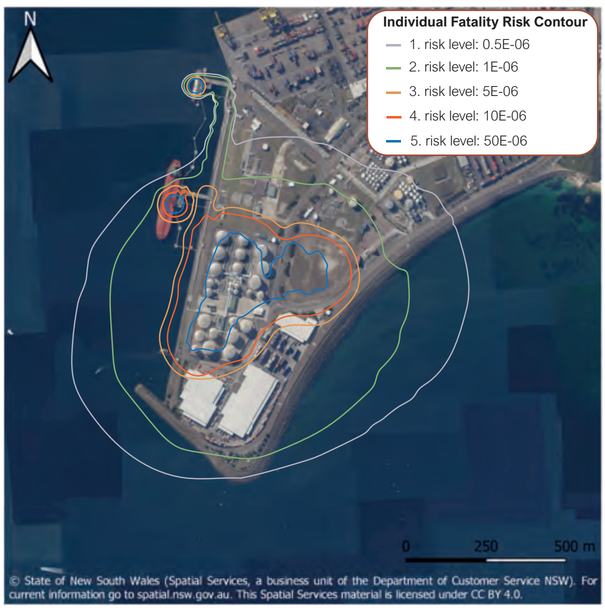


Figure 2.3: Individual fatality risk contours for an oil terminal, Port Botany, Australia (source: Spatial Service State of New South Wales, contours from Sherpa consulting, image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0.

The LNG example concerns a case of impact reduction, as the risk contours are likely to be translated to exclusion zones if a hazard occurs. Prevention of hazardous situations is another type of measure to increase port safety. Moored vessel motions, for instance, can not only hamper (un)loading operations, but can also lead to hazardous situations, such as snapping mooring lines. Instead of computing mooring line forces from ship motions derived from wave conditions, one uses experience-based wave height limits to decide whether a vessel should leave berth (Table 2.4).

2.2.2 Waterway performance

Like in the case of port water bodies, many rules for waterway dimensions are empirically based (see, for instance RVW, 2020). Rules of thumb can also serve to estimate the capacity of open waterways, i.e. without delays due to locks or bridges.

We define the intensity, I, of the traffic on a waterway as the number of vessels (or the tonnage) that pass a fixed cross-section per unit time at a given point in time (Figure 2.4). The maximum possible value of this instantaneous quantity is the waterway's capacity, C. The ratio I/C is called the traffic load. The number of vessels per unit area at the same time is the density, D.

Vessel type	**Limiting wave height H_s [m]**	
	0° (ahead or astern)	**45–90° (abeam)**
General cargo	1.0	0.8
Container, Ro-Ro	0.5	
Dry bulk (30,000 – 100,000 DWT), loading	1.5	1.0
Dry bulk (30,000 – 100,000 DWT), unloading	1.0	0.8 – 1.0
Tankers (30,000 – 200,000 DWT), loading	1.5 – 2.5	1.0 – 1.2
tankers (> 200,000 DWT)	2.5 – 3.0	1.0 – 1.5

Table 2.4: Limiting wave heights for moored vessels (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

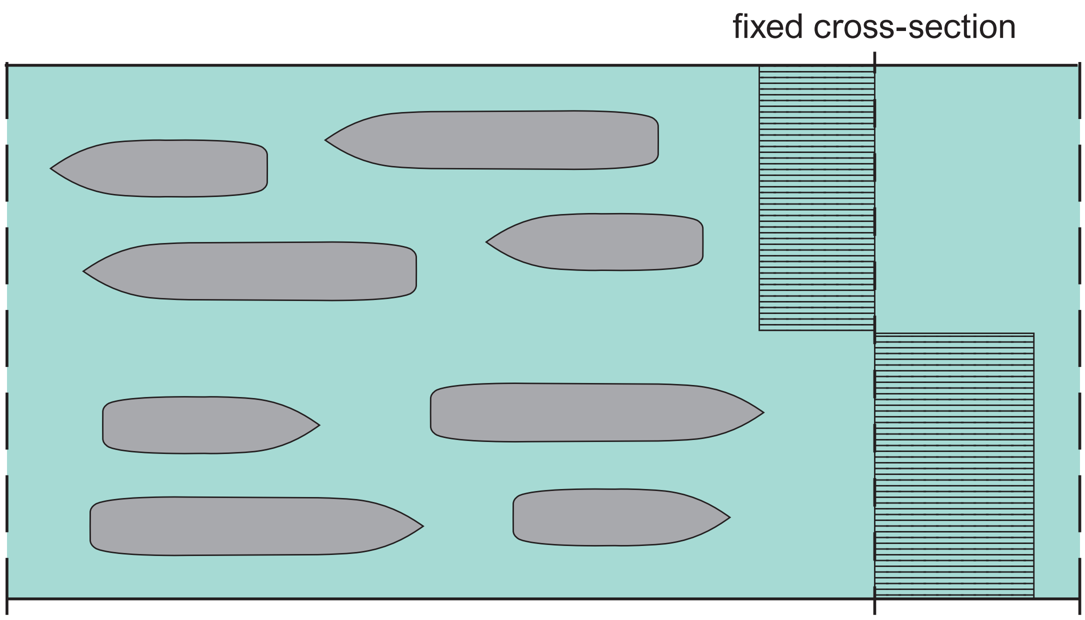


Figure 2.4: Traffic intensity on a waterway (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

On an open waterway, i.e. without any delays due to bridges or locks, this capacity is determined to a large extent by ship-waterway interactions (resistance, limit speed, economic speed) and ship-ship interactions (encounters, overtaking, blue-boarding, etc.).

Clearly, the vessel speed is a determining factor of a waterway's traffic intensity and capacity. This speed in influenced by the ship-waterway interaction, as well as by ship-ship interactions and economic considerations (fuel consumption). If we reduce the ship-ship interaction to a relationship between average vessel speed and traffic density, there is a complex interaction between the vessel speed V_s, the traffic density and the traffic intensity. This can be explained as follows (Figure 2.5):

- at very low traffic density, the vessels can sail without mutual interaction, at speed V_0;
- as the density increases, the velocity starts decreasing, but at such a rate that the traffic intensity still increases; the intensity in this situation is less than the waterway's capacity;
- this intensity increase continues until a maximum is reached; at that point, the velocity is V_{crit} and density D_{crit} ; the intensity is equal to the capacity here;
- as the density increases further, the ship speed decreases so strongly, that the intensity also starts decreasing, until it reaches zero at the density where sailing is no longer possible; in this situation the capacity decreases along with the intensity.

The relationship between vessel speed and traffic density can be determined either empirically or from model simulations. The intensity is the result of a calculation, viz. the product of vessel speed and traffic density.

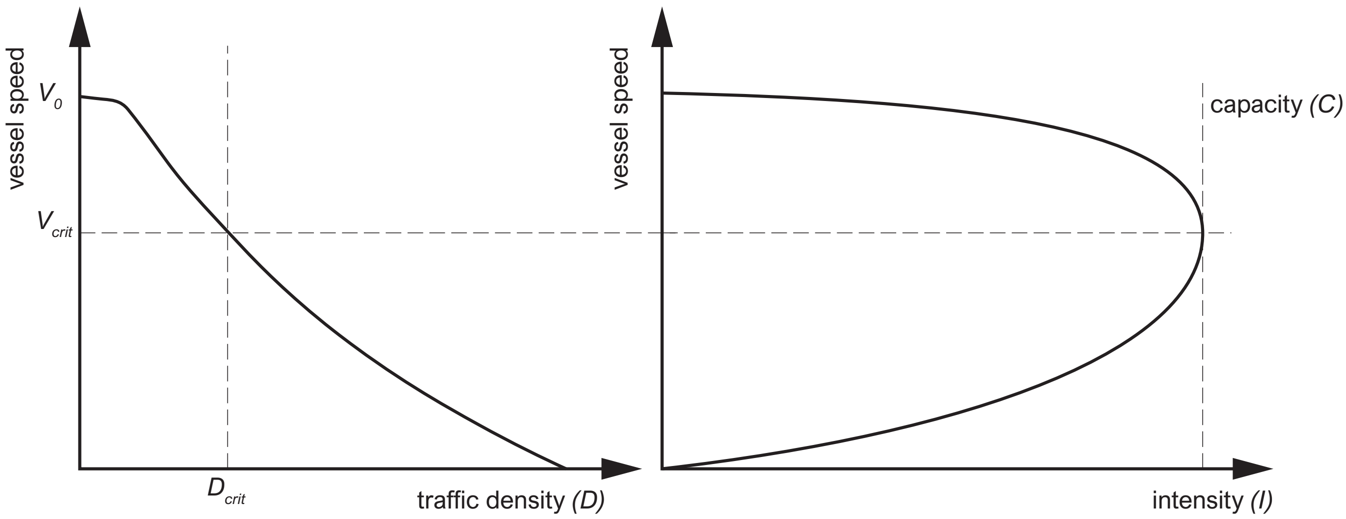


Figure 2.5: Relationship between vessel speed and traffic density, capacity and load (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

If we combine the curve for the traffic load with another largely empirical relationship, viz. between the vessel speed and the propulsion power required to sustain it (as a proxy of energy consumption and emissions), we can find what is called the economical speed (Figure 2.6). Note that this speed is larger than the critical speed, which corresponds with the highest throughput of the waterway. This means the operational optimum of an individual vessel differs from that of the waterway as a whole.

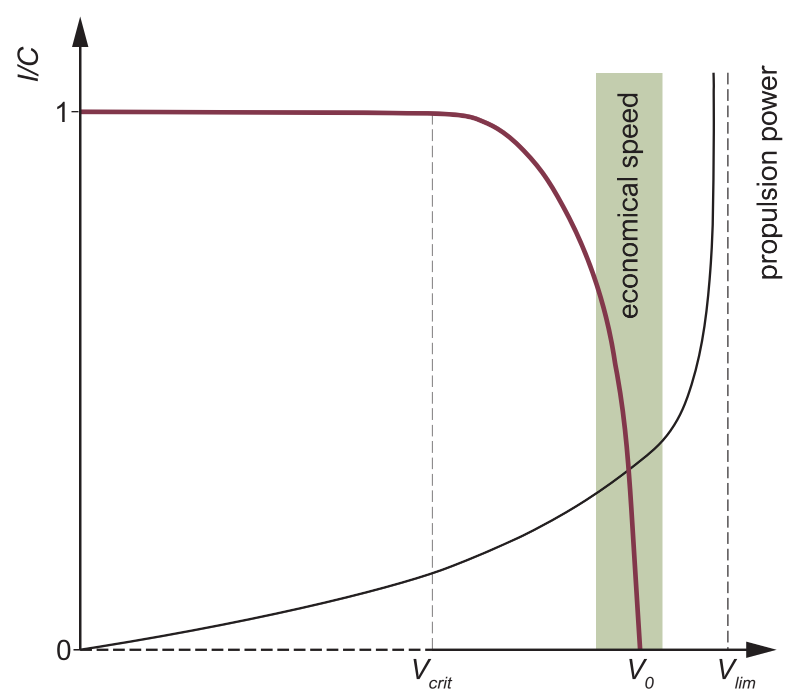


Figure 2.6: Economical vessel speed (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The maximum allowable traffic density and the capacity of open waterways are determined by simulation, or by assuming a virtual space around each vessel, taking into account the stopping distance and safety margins for ship-ship interactions (Figure 2.7).

The dimensions of this virtual space are determined with the aid of photographs from a radar screen. For simplicity, its shape is taken as rectangle, with length L_v and width B_v. These dimensions depend on the vessel size, the situation (straight reach, bend) and whether the vessel is sailing upstream or downstream. In the early 1970s Rijkswaterstaat performed an extensive study on vessel traffic at the river Waal (RWS, 1976). It led to the

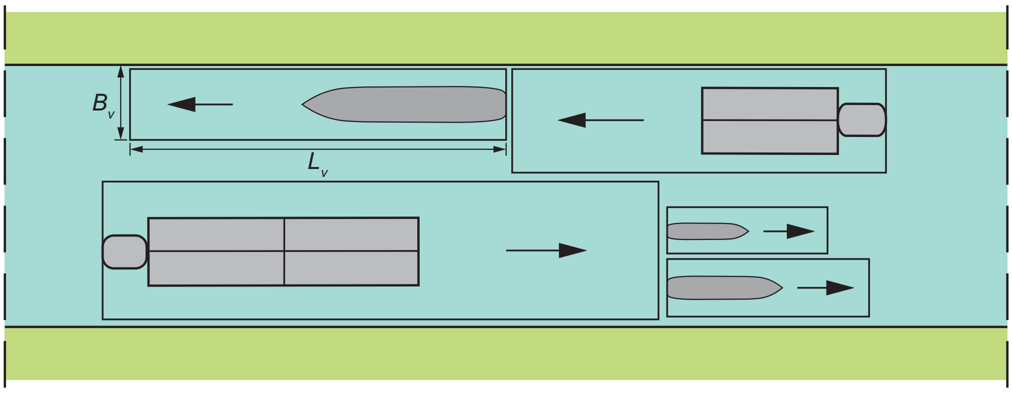


Figure 2.7: Virtual space to determine the waterway capacity (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

conclusion that L_v is proportional to the vessel length L_s, with a coefficient of proportionality of 1.45 if the vessel is sailing downstream, 1.05 when sailing upstream on a straight reach, and 1.25 when sailing upstream in a bend. Similarly, the width of the virtual area has been determined empirically for every vessel type, taking into account margins for safe navigation.

Safety margins like these, but also those included in waterway dimensions, bridge heights, etc., are by definition empirical, if only because the events against which they are supposed to protect are not exactly known. Yet, absolute safety cannot be guaranteed; there is always a residual risk.

So far, we have considered waterway performance from a fixed standpoint, looking at how many vessels or how much cargo can pass per unit time. Instead, one may also consider it from a skipper's standpoint: "How much time do I need to spend to sail from A to B?". This time spent (sometimes called the waterway's 'resistance') depends on the vessel's speed and waiting times at bridges and locks. The vessel's speed, in its turn, is influenced by the interaction with other vessels (see Figure 2.8 for an example), so the time spent is a function of the traffic. Given the traffic's variability and the complexity of the interactions, rules of thumb are the obvious way to take this into account.

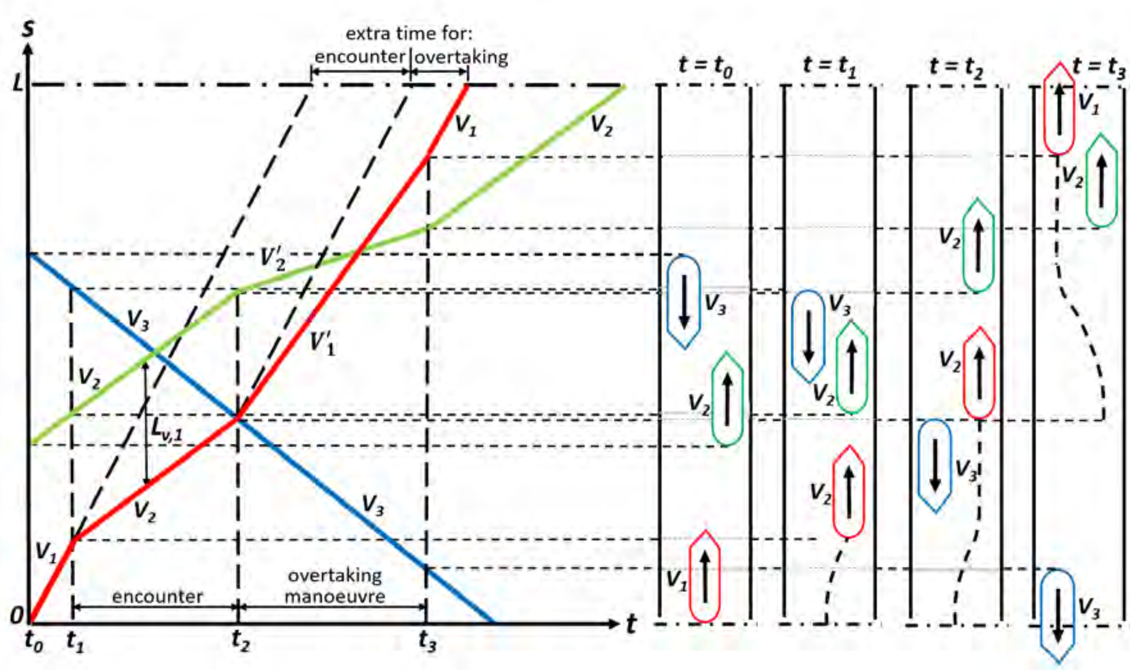


Figure 2.8: Vessel tracks during an encounter and an overtaking manoeuvre (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The delaying effect of ship-ship interactions also explains why droughts hit a waterway's transport capacity so hard. Not only do they reduce the possible draught, and thus the load capacity of the vessels, they also lead to a higher traffic intensity (more ships needed to transport the same amount of cargo), hence a further capacity reduction. A rule of thumb often used per vessel in case of low water is the load capacity reduction in relation to the draught reduction, e.g. 'every decimetre of draught reduction means a load capacity loss of 100 ton for a Class IV inland vessel'. Further see Section 4.1.1.

In many waterways there are obstacles such as bridges, weirs and locks, or other delaying elements such as bends or (temporary) obstacles. They generally take extra time or cause delays, because vessels have to make complex manoeuvres to pass a bridge (Figure 2.9), have to wait for other vessels before being able to pass a bridge, wait for movable bridges to open, need time to pass a lock, need manoeuvring to navigate a bend, et cetera.

Figure 2.9: Passing a bridge may require careful manoeuvring and take time (image by Quistnix is licenced under CC BY-SA 2.5).

2.2.3 Lock performance

Locks, if present, are usually determining factors for a waterway's capacity. This means that locks have to meet certain capacity requirements in order to comply with the other parts of the waterway. An extra complication is that many locks are not only used by cargo ships, but also by pleasure craft (Figure 2.10). Although cargo ships have priority, locking the pleasure craft inevitably takes extra time, so causes extra transport delays.

Figure 2.10: Locks are not only used by cargo ships (image by https://beeldbank.rws.nl, Rijkswaterstaat).

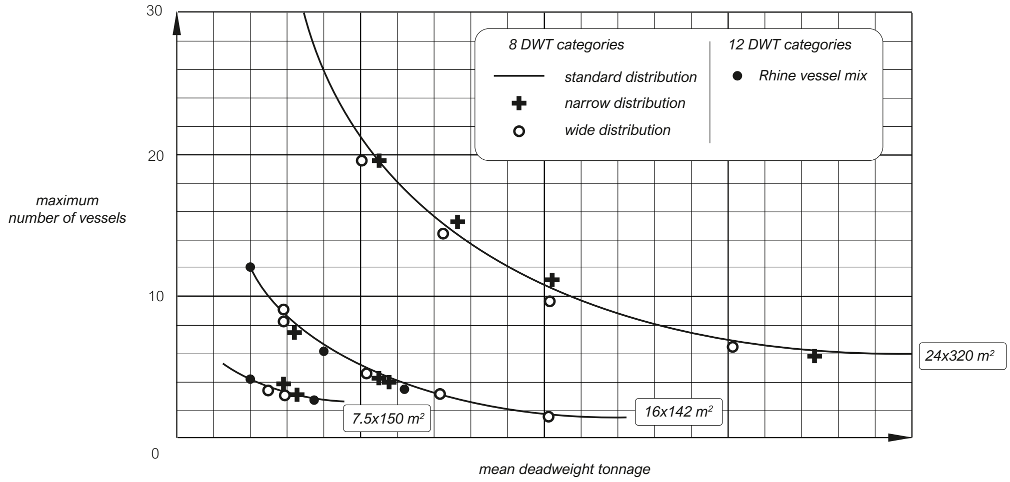


Figure 2.11: Maximum number of vessels in a lock chamber (reworked from Kooman and De Bruijn, 1975, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The investment involved in building a lock is too high for the design to be based on rules of thumb. Yet, empirical relationships can be of use in (pre)feasibility studies, to characterise existing lock systems, or for early warning of an upcoming capacity problem. A relevant design question is how many vessels fit into a lock chamber of a given size, given the vessel mix. As an example, Figure 2.11 shows observation-based relationships for various chamber sizes and various characteristic vessel mixes at the time.

Figure 2.12 shows an example of lock characterisation, for a lock in the river Maas near Heel (Netherlands). It shows the passage time as a function of the traffic load and for different arrival patterns. The underlying data have been produced with the Kooman model (Kooman and De Bruijn, 1975), which combines empirical rules with a look-up table from queueing theory. One may assume that these curves are characteristic of the waiting times at this lock as long as the vessel mix does not change.

If the traffic load is increasing, there comes a point where the maximum waiting time is exceeded. As this maximum corresponds with a rather low value of the traffic load, studying and planning of measures to increase the capacity have to start at a traffic load value where no problem may be suspected. Figure 2.13 shows the example of the Kreekrak locks in the Scheldt-Rhine Canal, which connects the port of Antwerp with the Rotterdam area. As a rule of thumb, capacity increase should start being considered at an I/C-value as low as 0.5.

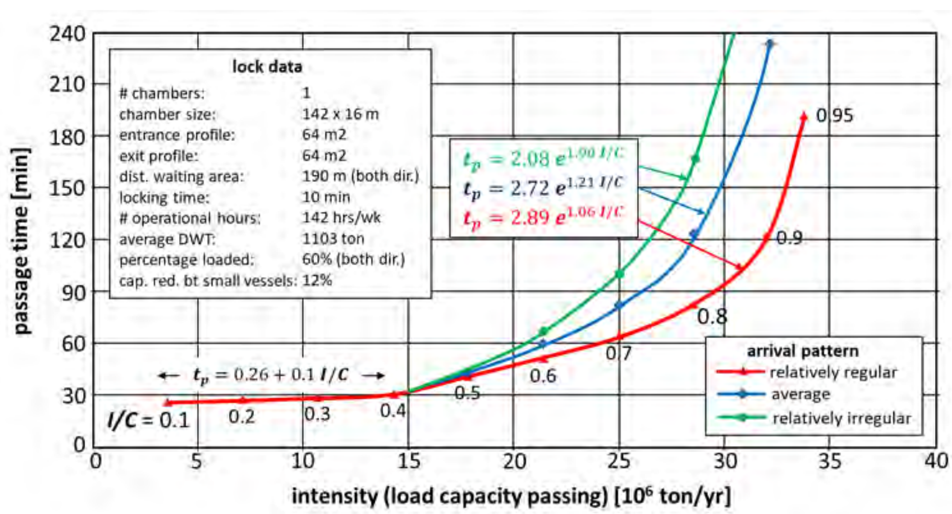


Figure 2.12: Passage times at the lock near Heel, NL (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

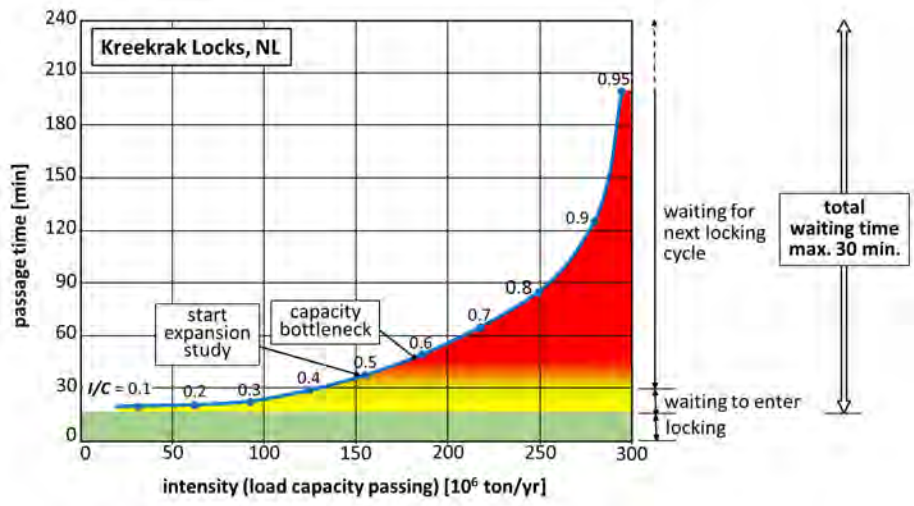


Figure 2.13: When to start considering capacity-increasing measures (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0)?

2.3 Analytical models

Analytical models are used in waterborne transport in a wide variety of forms. In general, they consist of a set of calculation rules or (differential) equations that can be handled analytically. The determination of the net present value of capital or operational expenditures (Part I – Section 2.2.4) is an example of a logic-based calculation rule, viz. the sum of a finite power series. Schijf's method to determine the water level set-down beside a ship sailing in confined water (Part III – Section 4.1) is an example of an analytical model based on conservation laws from classical physics. Simple forms of queueing theory can also be derived analytically, as we will show in this chapter.

A way of model classification is by the number of dimensions they involve. In the background of the NPV calculation there is a discrete representation of the dimension time (year by year). The equations underlying Schijf's model are one-dimensional in space and time, but by fixing the coordinate system to the moving vessel, the time dimension is eliminated. Time has also been eliminated from frequency-domain wave propagation models, which are one- or two-dimensional in space.

Models can be deterministic and stochastic. The NPV-calculation and Schijf's model are deterministic, while queueing theory starts from probability distributions and is therefore stochastic.

We have seen that waiting time limitations are of paramount importance to the design of ports and waterways. One of the ways to deal with this is queueing theory. Therefore, we will first focus on an analytical form of this often-used tool.

2.4 Queueing theory and Kendall's notation

The origin of queueing theory is attributed to the Danish engineer Agner Krarup Erlang (1878-1929). His work on modelling the capacity of telephone networks (Erlang, 1909) laid the theoretical foundation for modern telecommunication networks. Queueing theory focuses on systems with customers arriving at random (with a given probability distribution $Pr\{A\}$) and staying in the system until they have been served. These services also have a random character with a given probability distribution $Pr\{S\}$.

Typical aspects that are described by queueing models are:

- L_s: the long-term average number of customers present in the system,
- L_q: the long-term average number of customers waiting in the queue,
- W_s: the long-term average time present in the system, and
- W_q: the long-term average waiting time in the queue.

Queueing systems can be characterised by the stochastic properties of arrivals, those of the services and the number of servers (e.g. berths on a quay). Further aspects that distinguish the systems we look at are the number of places in the system (finite or infinite), the size of the calling population (finite or infinite) and the queue discipline (often First In First Out, but other disciplines may apply).

Kendall (1953) defined a classification method to distinguish between different types of queueing systems, using the notation ($A/S/c$: $K/N/D$), with:

- A: the arrival process, with a random distribution of the inter-arrival time marked by a letter code,
- S: the service process, with a random distribution of the service time, marked by another letter code,
- c: the number of servers,
- K: the number of places in the system,
- N: the number of individuals in the calling population,
- D: the queue discipline.

The simplest queueing system assumes both arrivals and services to be Markovian (marking letter M), which means that their respective probabilities do not depend on past states (memoryless). Note, however, that queueing systems are not always Markovian, in which case more complex (numerical) computations are needed.

For a few queueing systems analytical solutions can be derived from first principles. We will show this for one of them, with Kendall notation ("$M/M/1$: ∞/∞/FIFO"), i.e.. Markovian arrival and service processes, one server, an infinite number of places, an infinite calling population and a First In First Out queue discipline.

2.4.1 Arrival, service and queueing processes

Arrival process

Vessels waiting to enter a port, form a good example where queueing theory can be applied (Figure 2.14).

Figure 2.14: Ships queueing for the Port of Singapore (image by shawnanggg is free to use under the Unsplash Licence).

In general, the arrival process of ships calling at port is of a stochastic nature and arrival times are stochastically independent, i.e. future arrivals don't depend on arrivals in the past. Such stochastic processes are called Poisson processes. The most convenient way of representing the arrival process is to look at the intervals between successive arrivals at the port, the interarrival times. Table 2.5 and Figure 2.16 give an example of interarrival times, taking hourly intervals and assuming all arrivals to take place within 8 hours.

inter arrival time	number	%	cumulative %
2h	3	5	5
3h	10	17	22
4h	12	20	42
5h	15	25	67
6h	14	23	90
7h	5	8	98
8h	1	2	100

Table 2.5: Example of interarrival times (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

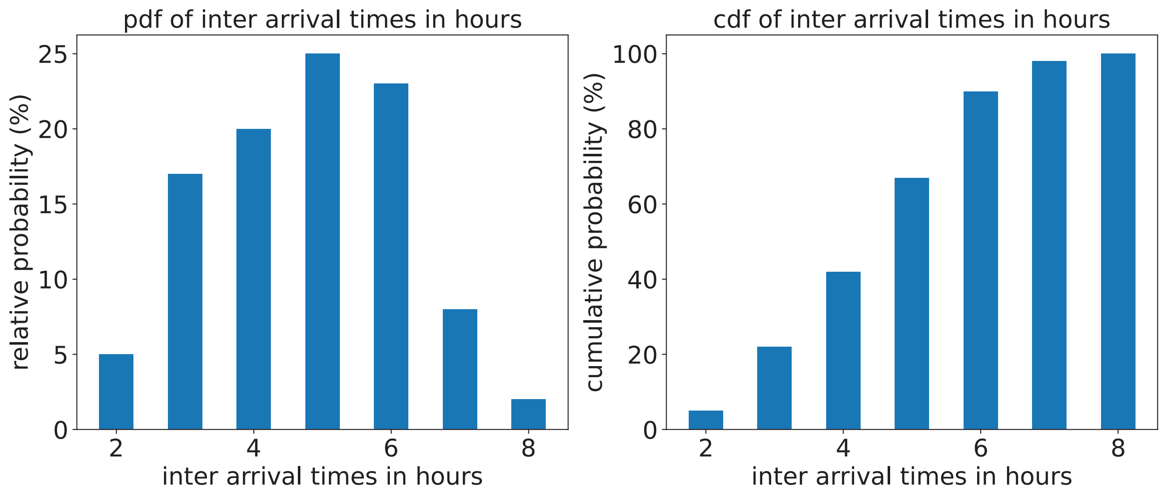


Figure 2.15: Relative probability and cumulative distribution of the interarrival times as in Table 2.5 (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Probability distributions are usually given in the form of a continuous or discrete probability distribution function (pdf), which relates the relative probability of occurrence to an independent variable, in this case time. By definition, the time-integral of a continuous pdf, as well as the infinite sum of a discrete pdf, equals 1.

Interarrival times in a Poisson process are typically exponentially distributed (Markov-process). This means that the probability that the interarrival time T lies between s and t is given by

$$Pr\{s < T \leq t\} = e^{-\lambda s} - e^{-\lambda t} \tag{2.2}$$

where λ is the average arrival rate. i.e. the average number of arrivals per unit time. The corresponding pdf reads

$$f(t) = \lambda e^{-\lambda t} \ (t > 0) \tag{2.3}$$

The average interarrival time can be derived from

$$\overline{T} = \int_0^\infty t f(t) dt = \frac{1}{\lambda} \tag{2.4}$$

If N is the number of arrivals in a time interval of fixed length t, then this discrete random variable has the Poisson distribution and the probability that $N = k$ follows from:

$$Pr\{N = k\} = e^{\lambda t} \frac{(\lambda t)^k}{k!} \tag{2.5}$$

Figure 2.16 gives examples of continuous exponential and discrete Poisson distributions.

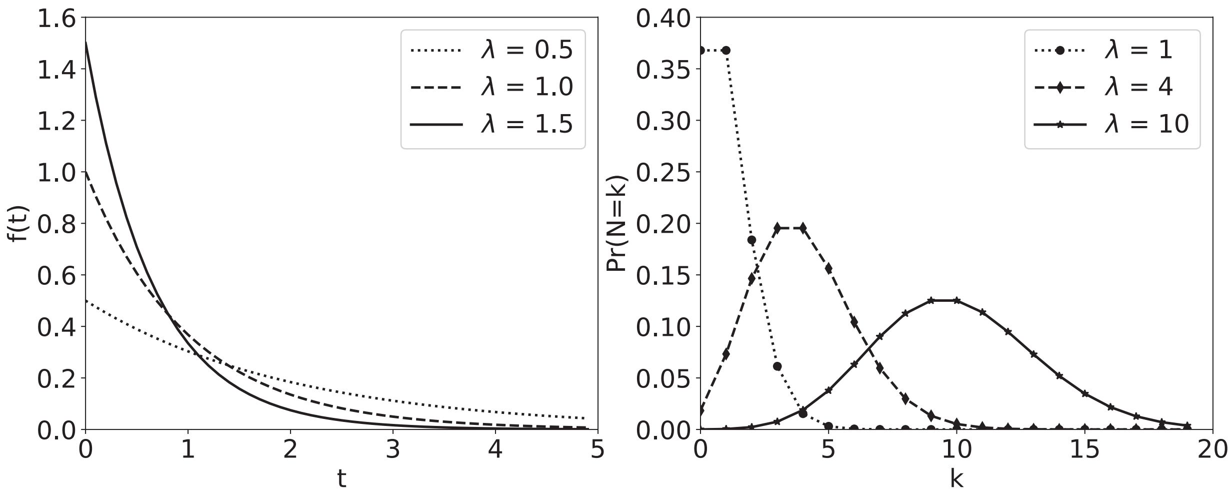


Figure 2.16: Continuous exponential distributions (left) and discrete Poisson distributions (right) (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Service process

The time taken to serve ships on a berth obviously influences the length of the queue that may form. Even a system with sufficient berths to meet the average arrival rate of ships will still experience queue formation from time to time.

Considering service times as a random process, their probability distribution needs to be known before a study can be made. In port systems the total service time often consists of several different stages, each with its own probability distribution. If we assume each stage to have a negative exponential distribution with parameter $k\lambda$, the combination of stages is described by the Erlang-k distribution (Kendall's notation E_k):

$$f(t) = \frac{(k\mu)^k t^{k-1}}{(k-1)!} e^{-k\mu t} \text{ for:} t > 0 \tag{2.6}$$

in which μ is the average service rate per berth and $1/\mu$ the average total service time, i.e. the expected value of the sum of service times of the different stages. By changing the parameter k one can fit this distribution to observations (Figure 2.17). Taking $k = 1$ yields the negative exponential distribution of Equation 2.3.

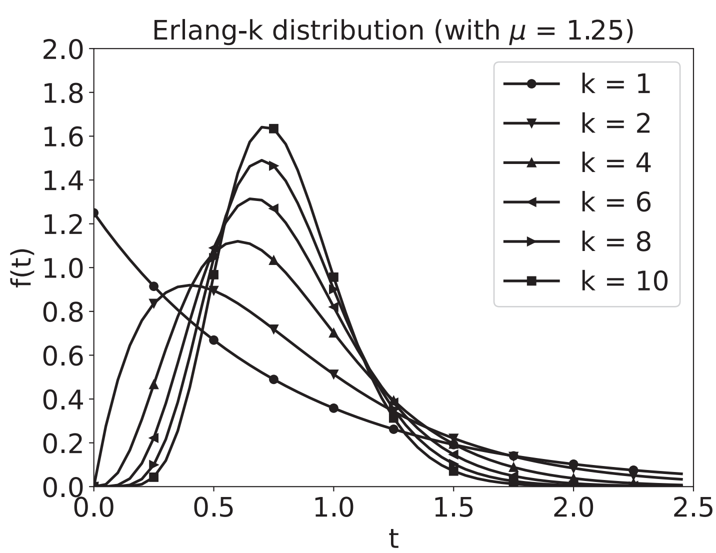


Figure 2.17: Erlang-k distributions for different values of k (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Queueing

In situations where a queue of several customers has been formed there must be some way of deciding which customer (ship) is to be served next. Firstly, there are basically two different types of queues (Figure 2.18): in a row for each server (multiple queues), or in a single line for all servers (single queue). Here we will consider the latter form.

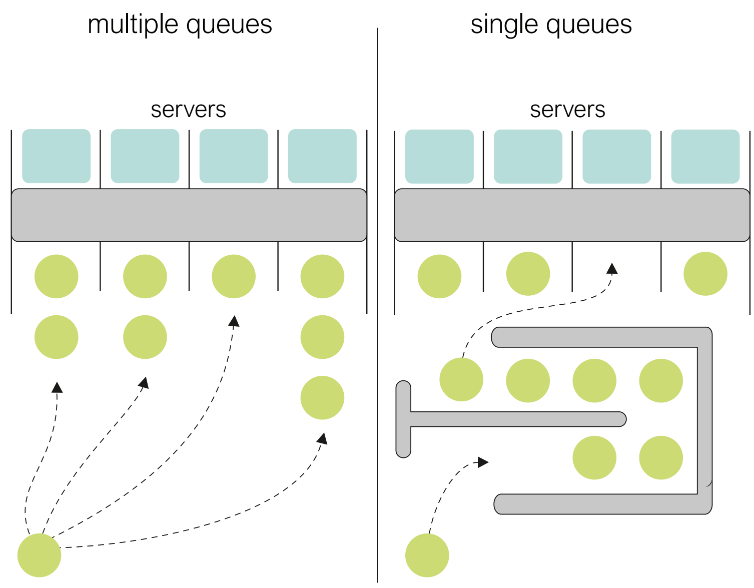


Figure 2.18: Two forms of queueing (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

In single-line queueing there are various rules (queue disciplines) to determine who is served next:

1. on the basis of arrival time,
   - First In First Out (FIFO) / First Come First Serve (FCFS),
   - Last In First Out (LIFO) / Last Come First Serve (LCFS),,
   - Service In Random Order (SIRO),
2. on the basis of service time requirement,
   - Shortest Processing Time First (SPTF),
3. on the basis of priority.
   - Priority Queueing (PQ),
   - et cetera.

Depending on the performance of a queueing system, customers may display various types of behaviour:

- *Balking* – when a customer perceives the waiting times to be too long, they may decide not to join the queue, and as a consequence not become part of the queueing system,
- *Jockeying* – when a customer decides to switch between queues in the anticipation that they will be served faster, and
- *Reneging*: when customers have already entered the queueing system, but decide to leave if they have waited too long.

Figure 2.19 shows the how the probability of the waiting time to exceed a certain value t varies with the queueing discipline. Clearly, the variance of a LIFO discipline is larger than that of a FIFO arrangement.

A port or terminal operator will try to organise the port/terminal operations in such a manner, that customers will perceive the service to be of satisfactory quality. Just like for retail stores, customers may look for alternatives when they feel that service levels are insufficient. Once customers have made the switch to an alternative terminal it can be hard to win them back. It is for this reason that queueing models are often used in the evaluation of (future) performance.

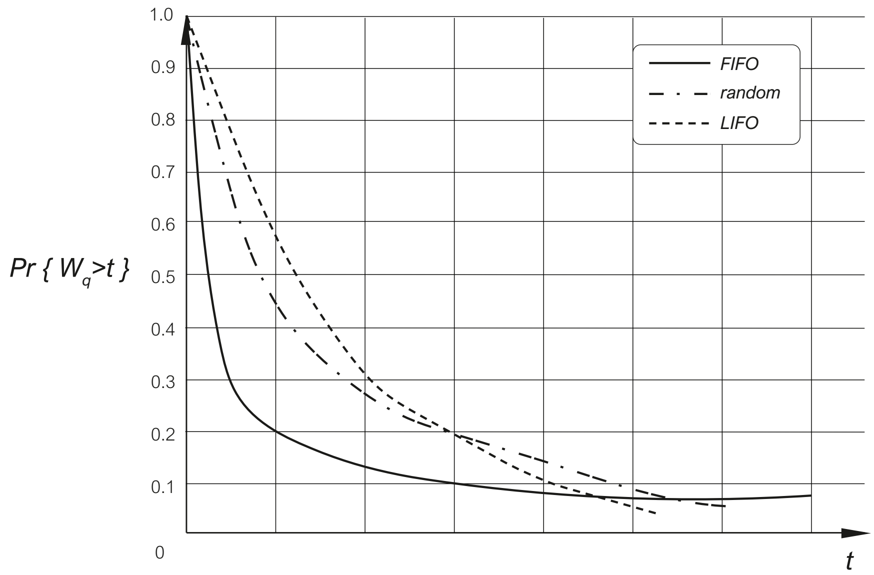


Figure 2.19: Effect of queue disciplines on waiting times (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

2.4.2 (“$M/M/1$: ∞/∞/FIFO”) queueing theory

When a ship approaches a port, it is not obvious that it can be served immediately. The port operator has to negotiate between the capital and operational costs of the port and the waiting time for incoming ships. Since ships arrive generally at random, service without waiting times would be economically suboptimal. On the other hand, too long waiting times make the port less attractive to shipping lines. Clearly, these conflicting interests call for optimisation.

If a ship requires only a single service point and a single service before departing again, the factors determining the system’s behaviour are (see Figure 2.20):

1. ship arrivals,
2. the service time per ship,
3. the service system (queue discipline, number of berths)

The queueing system requires specifying the statistics of the arrival and service processes and the number of berths in the system. For “$M/M/1$: ∞/∞/FIFO”-queues an analytical solution can be derived.

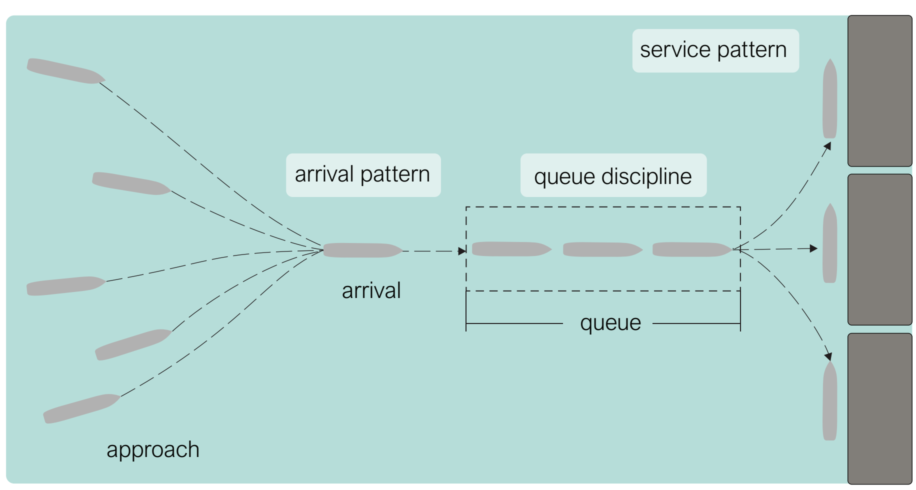


Figure 2.20: Schematic of a port service system (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Box model

We start with the general box model formulation (see Figure 2.21 and Equation 2.7):

Figure 2.21: Box model of a queueing system (modified from image by Tsaitgaist, by TU Delft – Ports and Waterways is licenced under CC BY-SA 3.0).

$$\frac{\partial f}{\partial t} = F_{in} - F_{out} + P_f - D_f \tag{2.7}$$

When it comes to queueing systems, the abstract property f is taken to be the number of customers n present in the system. The flux of customers entering the system, F_{in}, is represented by the rate of arrivals (arrivals per hour). The flux of customers leaving the system, F_{out}, is represented by service rate μ (departures per hour). Assuming no customers are dissipated or produced inside the system, this would result in the following balance equation:

$$\frac{\partial n}{\partial t} = \lambda - \mu \tag{2.8}$$

Stochastic formulation of the balance equation

Equation 2.8 simply states that the change in the number of customers in the system is determined by the difference between the number of customers arriving and those leaving after having been served. This intuitive logic is easy to follow when the actual values of $n(t)$, λ, μ and the time step are known. In queueing theory, however, one of the challenges is that arrival rates and service times are mostly stochastic rather than deterministic. We will therefore rewrite Equation 2.8 using stochastic variables and look at the probability that at time t there are n customers in the system, $P_n(t)$. Using the box model approach we can now describe the system by:

$$\begin{aligned} P_n(t+h) = \cdots & \\ & P_{n-1}(t) \cdot P(arr. = 1) \cdot P(dep. = 0) + \cdots \\ & P_n(t) \cdot P(arr. = 0) \cdot P(dep. = 0) + \cdots \\ & P_n(t) \cdot P(arr. = 1) \cdot P(dep. = 1) + \cdots \\ & P_{n+1}(t) \cdot P(arr. = 0) \cdot P(dep. = 1) \end{aligned} \tag{2.9}$$

Basically, Equation 2.9 states that the probability that at time $t + h$ there are n customers in the system is equal to:

- the probability that $n - 1$ people are present at t, times the probability that during time step h 1 arrival and 0 departures take place,
- plus the probability that n people are present at t, times the probability that during time step h 0 arrivals and 0 departures take place,
- plus the probability that n people are present at t, times the probability that during time step h 1 arrival and 1 departure take place,
- plus the probability that $n + 1$ people are present at t, times the probability that during time step h 0 arrivals and 1 departure take place.

We further assume that time step h is so small that only one event can take place. As a consequence, the combination of 1 arrival *and* 1 service cannot take place during the same time step h. Note, furthermore, that the probability of 1 arrival during h is λh, whereas the probability of 0 arrivals is $(1-\lambda h)$. Likewise, the probability of 1 service during h is μh, and the probability of 0 services is $(1-\mu h)$. We can now rewrite Equation 2.9 to:

$$\begin{aligned} P_n(t+h) = \cdots \\ & P_{n-1}(t)\cdot\lambda h\cdot(1-\mu h)+\cdots \\ & P_n(t)\cdot(1-\lambda h)\cdot(1-\mu h)+\cdots \\ & P_{n+1}(t)\cdot(1-\lambda h)\cdot\mu h \end{aligned} \tag{2.10}$$

Performing algebraic operations and neglecting higher order terms yields:

$$\begin{aligned} P_n(t+h) = \cdots \\ & P_{n-1}(t)\lambda h - \underbrace{P_{n-1}(t)\lambda\mu h^2}_{neglect} + \cdots \\ & P_n(t) - P_n(t)\lambda h - P_n(t)\mu h + \underbrace{P_n(t)\lambda\mu h^2}_{neglect} + \cdots \\ & P_{n+1}(t)\mu h - \underbrace{P_{n+1}(t)\lambda\mu h^2}_{neglect} \end{aligned} \tag{2.11}$$

Rearranging yields:

$$\begin{aligned} \frac{P_n(t+h)-P_n(t)}{h} = \cdots \\ & P_{n-1}(t)\lambda - P_n(t)(\lambda+\mu) + P_{n+1}(t)\mu \end{aligned} \tag{2.12}$$

For model aspects L_s, L_q, W_s and W_q we are interested in long-term averages, or steady states. We will therefore apply the steady state assumption, meaning that probabilities are no longer time dependent and $\frac{P_n(t+h)-P_n(t)}{h}=0$. Applying this to Equation 2.12 yields the following equation:

$$P_n(\lambda+\mu) = P_{n-1}\lambda + P_{n+1}\mu \tag{2.13}$$

which relates the probability that n customers are in the system to the probabilities that $n-1$ and $n+1$ customers are in the system.

The limit case of zero customers in the system

We will now consider the limit case of zero customers in the system. First again in words:

$$\begin{aligned} P_0(t+h) = \cdots \\ & P_1(t)\cdot P(arr.=0)\cdot P(dep.=1)+\cdots \\ & P_0(t)\cdot P(arr.=0)\cdot P(dep.=0) \end{aligned} \tag{2.14}$$

Converting this into mathematical formulations yields:

$$\begin{aligned} P_0(t+h) = \cdots \\ & P_1(t)\cdot(1-\lambda h)\cdot\mu h + \cdots \\ & P_0(t)\cdot(1-\lambda h)\cdot 1 \end{aligned} \tag{2.15}$$

Logically, the probability of 'no service' must be 1 if there are no customers in the system. Performing algebraic operations and again neglecting second-order terms yields:

$$\begin{aligned} P_0(t+h) = \cdots \\ & P_1(t)\mu h - \underbrace{P_1(t)\lambda\mu h^2}_{neglect} + \cdots \\ & P_0(t) - P_0(t)\lambda h \end{aligned} \tag{2.16}$$

After rearrangement this yields:

$$\begin{aligned} \frac{P_0(t+h)-P_0(t)}{h} = \cdots \\ & P_1(t)\mu - P_0(t)\lambda \end{aligned} \tag{2.17}$$

Since in the steady state the time-variation of P_0 equals zero, we can rewrite Equation 2.17 into:

$$P_1\mu = P_0\lambda \tag{2.18}$$

whence:

$$P_1 = \frac{\lambda}{\mu}P_0 \tag{2.19}$$

Combining the zero-customer condition with the general equation

Resuming Equation 2.13

$$P_n(\lambda+\mu) = P_{n-1}\lambda + P_{n+1}\mu$$

and substituting $n = 1$ while making use of Equation 2.19 yields:

$$P_1(\lambda+\mu) = P_0\lambda + P_2\mu$$

This can be rewritten to:

$$P_1\lambda + P_1\mu = P_0\lambda + P_2\mu \tag{2.20}$$

If we substitute Equation 2.18 we get:

$$P_1\lambda + P_0\lambda = P_0\lambda + P_2\mu$$

which can be rewritten to:

$$P_2 = \frac{\lambda}{\mu} P_1 \tag{2.21}$$

With Equation 2.19 this can be rewritten to:

$$P_2 = \left(\frac{\lambda}{\mu}\right)^2 P_0 \tag{2.22}$$

The ratio λ/μ is commonly replaced by the symbol ρ. If we do so we can show that:

$$\begin{aligned} P_1 &= \rho P_0 \\ P_2 &= \rho P_1 = \rho^2 P_0 \\ P_3 &= \rho P_2 = \rho^3 P_0 \\ P_n &= \rho^n P_0 \end{aligned} \tag{2.23}$$

Finding the value of P_0

Equation 2.23 shows that the value of P_0 is the key to all other probabilities P_n. We can find P_0 by applying the integral property:

$$\begin{aligned} \sum_{n=0}^{\infty} P_n &= 1 \\ P_0 + P_1 + P_2 + \cdots \infty &= 1 \\ P_0 + \rho P_0 + \rho^2 P_0 + \cdots \infty &= 1 \\ P_0 \left[1 + \rho + \rho^2 + \rho^3 + \cdots \infty\right] &= 1 \end{aligned} \tag{2.24}$$

In this equation the expression:

$$\left[1 + \rho + \rho^2 + \rho^3 + \cdots \infty\right]$$

is a so-called infinite geometric series. In other words there is a fixed ratio between the successive terms into infinity; in this case that ratio is ρ. In general terms an infinite geometric series can be written as:

$$a + ar + ar^2 + ar^3 + \cdots \infty = \sum_{k=0}^{\infty} ar^k$$

The result of the infinite summation is:

$$\sum_{k=0}^{\infty} ar^k = \frac{a}{1-r}$$

as long as $|r| < 1$.

In Equation 2.24 the general variable r corresponds with ρ and the value of a is equal to 1. A fundamental requirement for the "M/M/1: ∞/∞/FIFO" type models, where the calling population size is infinitely large, is that the long-term average arrival rate should be smaller than the long-term average service rate, or in other words $\lambda/\mu = \rho < 1$. With this requirement satisfied, the infinite geometric series in Equation 2.24 can be replaced:

$$\left[1+\rho+\rho^2+\rho^3+\cdots\infty\right]=\frac{1}{1-\rho}$$

enabling us to rewrite Equation 2.24 to:

$$\begin{aligned}
&P_0\left[1+\rho+\rho^2+\rho^3+\cdots\infty\right]=1\\
&P_0\left[\frac{1}{1-\rho}\right]=1\\
&P_0=1-\rho
\end{aligned}\tag{2.25}$$

With this we can now expand and rewrite Equation 2.23 to:

$$\begin{aligned}
&P_0=1-\rho\\
&P_1=\rho P_0=\rho(1-\rho)\\
&P_2=\rho^2P_0=\rho^2(1-\rho)\\
&P_3=\rho^3P_0=\rho^3(1-\rho)\\
&P_n=\rho^nP_0=\rho^n(1-\rho)
\end{aligned}\tag{2.26}$$

This means that for an M/M/1 model in fact the value of ρ suffices to determine P_0, P_1 up to P_n.

Deriving expressions for queue length and residence times

The first aspect for which we will derive an expression is the number of customers n expected to be present in the system, L_s. L_s is defined as the sum for $n=1,2,\cdots\infty$ of the product nP_n. Rewriting in terms of P_0, bringing P_0 outside the summation, rewriting with a differential and reordering to reveal an infinite geometric series (!), rewriting, integrating and rewriting again, reveals that L_s can be expressed as a function of ρ:

$$\begin{aligned}
L_s=\sum_{n=0}^{\infty}nP_n&=\sum_{n=0}^{\infty}n\rho^nP_0\\
&=\rho P_0\sum_{n=0}^{\infty}n\rho^{n-1}\\
&=\rho P_0\sum_{n=0}^{\infty}\frac{d}{d\rho}\rho^n\\
&=\rho P_0\frac{d}{d\rho}\sum_{n=0}^{\infty}\rho^n\\
&=\rho P_0\frac{d}{d\rho}\left[1+\rho+\rho^2+\cdots\infty\right]\\
&=\rho P_0\frac{d}{d\rho}\frac{1}{1-\rho}\\
&=\rho P_0\frac{1}{(1-\rho)^2}\\
&=\frac{\rho(1-\rho)}{(1-\rho)^2}\\
&=\frac{\rho}{1-\rho}
\end{aligned}\tag{2.27}$$

The long-term average number of customers in the system, L_s, is equal to the long-term average of the number the queue plus the number being served. The probability that there are no customers in the system is P_0, so the probability that customers are being served is $1 - P_0 = \rho = \lambda/\mu$. Since only one customer at a time can be served, this means that the long-term average number of customers being served is also λ/μ. Hence:

$$L_s = L_q + \frac{\lambda}{\mu} \tag{2.28}$$

The long-term average number of customers in the system, L_s, can also be obtained by multiplying by the average customer arrival rate, λ, with the long-term average time that a customer spends in the system, W_s:

$$L_s = \lambda W_s \tag{2.29}$$

Similarly, the long-term average number of customers in the queue, L_q, can be obtained by multiplying by the average customer arrival rate, λ, with the long-term average time that a customer spends in the queue, W_q:

$$L_q = \lambda W_q \tag{2.30}$$

Equation 2.29 and Equation 2.30 are known as Little's equations and reflect Little's theorem. This states that the average number of customers in a system is equal to the average customer arrival rate times the average time that customers spend in the system. It is quite remarkable that this result does *not* depend on factors such as the distribution of arrivals and services, the size of the customer population, et cetera.

Summary

In summary, the following equations are of interest when working with "M/M/1: 1/1/FIFO" systems:

$$P_0 = 1 - \rho \tag{2.31}$$
$$P_n = \rho^n P_0 \tag{2.32}$$
$$L_s = \frac{\rho}{1-\rho} \tag{2.33}$$
$$L_q = L_s - \frac{\lambda}{\mu} = \frac{\rho^2}{1-\rho} \tag{2.34}$$
$$W_s = \frac{L_s}{\lambda} \tag{2.35}$$
$$W_q = \frac{L_q}{\lambda} \tag{2.36}$$

The probability that there are 0, 1 or n customers in the system can be used to establish utilisation rates. Note that the sum of all these probabilities is 1.

P_0 gives the probability that there are 0 customers in the system. The system's utilisation rate is determined by the probability that the number of customers is greater than 0:

$$\begin{aligned} P_{n>0} &= 1 - P_0 \\ &= 1 - (1 - \rho) \\ &= \rho \end{aligned} \tag{2.37}$$

The utilisation rate of the queue can be derived from the probability that there is at least 1 person in the queue, i.e. the probability that the number of customers in the system is greater than 1 (one being served):

$$\begin{aligned} P_{n>1} &= 1 - P_0 - P_1 \\ &= 1 - (1-\rho) - \rho(1-\rho) \\ &= \rho - \rho + \rho^2 \\ &= \rho^2 \end{aligned} \tag{2.38}$$

Example box 2.1: Example economic optimization

1. Case
A transhipment company owns one berth at a port.

Ships arrive for unloading every 12 hours on average, with a negative exponential distribution of interarrival times, so

$\lambda = 1/12 \text{ hr}^{-1}$

Ship sizes vary widely, yielding negative exponential distribution of serves times T, with parameter $\mu = 1/T$ (to be determined)

The running costs RC of a berth are inversely proportional to the service time:

$RC = 10{,}000\ \mu$ \$/day

Delay costs are 1,000 \$ per ship per day.

2. Objectives
To determine:

- the most economical unloading time,
- the corresponding average berth occupancy, and
- the average delay per ship.

3. Solution
Daily running costs: $10{,}000\ \mu$

Average number of ships/day: 2

Average delay per ship: $\frac{\rho}{\mu(1-\rho)}$ hours, with $\rho = \frac{1}{12\mu}$

Delay costs per day: $2\frac{\rho}{\mu(1-\rho)}\frac{1000}{24}$ \$/day

Total daily costs: $10{,}000\ \mu + \frac{2{,}000}{24\mu(12\mu-1)}\$/\text{day} = \frac{10{,}000}{T} + \frac{2{,}000T^2}{24(12-T)}$

Economic optimum: $d(\text{costs})/dT = 0$

Hence: $T^4 - 24T^3 + 120T^2 - 2,889T + 17,280 = 0$

Only one root makes sense: $T = 6.163 \text{ hr}^{-1}$

Correspondingly, $\mu = 0.163 \text{ hr}^{-1}$ and $\rho = 0.511$

Optimum berth occupancy: $100\rho = 51.1$ %

Long-term average delay per ship: $\frac{\rho}{\mu(1-\rho)} = \frac{0.511 \cdot 6.136}{1-0.511} = 6.29$ hrs $= 0.26$ days

Probability that on arriving, ship has no delay: $\mu(1-\rho) = \frac{0.489}{6.136} = 0.08$, so only 8%

Example box 2.1 – continued on next page

Example box 2.1 – continued from previous page

Average number of ships in the system: $\frac{\rho}{1-\rho} = \frac{0.511}{0.489} = 1.04$

Average number of ships in the queue: $\frac{\rho^2}{1-\rho} = 0.53$

The example shows that, although the average service time per ship is nearly half of the average interarrival time, the probability that a ship can be served immediately is only 8%. This is, of course, due to the random nature of the arrival and service processes.

2.4.3 More complex systems

The "M/M/1: ∞/∞/FIFO" system analysed in the previous section gives results that are uniquely related to ρ and λ. Analytical solutions are also possible for certain other combinations, such as "M/M/n: ∞/∞/FIFO" for a larger number of berths (see Table 2.6; note that for $n = 1$ the results agree with those above).

Berth occup. (ρ/n)	**Number of berths** n									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
10 %	0.1111	0.0101	0.0014	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
20 %	0.2500	0.0417	0.0103	0.0030	0.0010	0.0003	0.0001	0.0000	0.0000	0.0000
30 %	0.4286	0.0989	0.0333	0.0132	0.0058	0.0027	0.0013	0.0006	0.0003	0.0002
40 %	0.6667	0.1905	0.0784	0.0378	0.0199	0.0111	0.0064	0.0039	0.0024	0.0015
50 %	1.0000	0.3333	0.1579	0.0870	0.0521	0.0330	0.0218	0.0148	0.0102	0.0072
60 %	1.5000	0.5625	0.2956	0.1794	0.1181	0.0819	0.0589	0.0436	0.0330	0.0253
70 %	2.3333	0.9608	0.5470	0.3572	0.2519	0.1867	0.1432	0.1128	0.0906	0.0739
80 %	4.0000	1.7778	1.0787	0.7455	0.5541	0.4315	0.3471	0.2860	0.2401	0.2046
90 %	9.0000	4.2632	2.7235	1.9693	1.5250	1.2335	1.0285	0.8796	0.7606	0.6687

Table 2.6: Average waiting time/service time ratio in an "M/M/n: ∞/∞/FIFO" queueing system (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The expressions resulting from these analyses, however, soon become rather complicated. Results are therefore

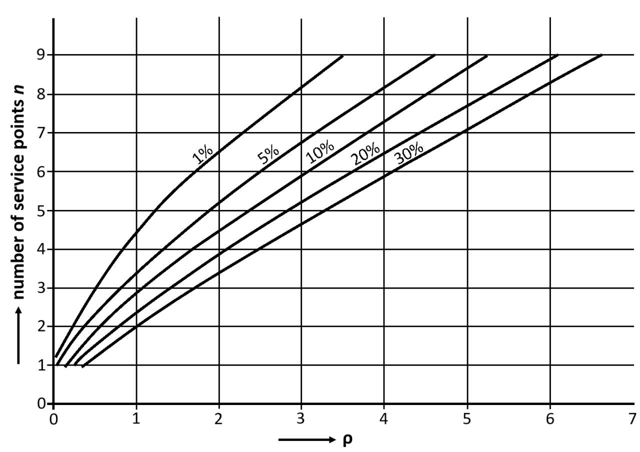


Figure 2.22: Probability that an arriving ship has to wait before being served (queueing system "M/M/n: ∞/∞/FIFO") (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

often presented in the form of look-up tables or graphs (see the examples in Example box 2.1 and Figure 2.22).

Example box 2.2: Summary of the M/M/n system

Summary of the M/M/n-system
Probability that the system is empty:

$$P(0) = \left[1 + \rho + \frac{\rho^2}{2!} + \cdots + \frac{\rho^{n-1}}{(n-1)!} + \frac{\rho^n}{n!}\frac{n}{n-\rho}\right]^{-1} = \left[\sum_{j=0}^{n-1} \frac{\rho^j}{j!} + \frac{\rho^n}{n!}\frac{n}{n-\rho}\right]^{-1}$$

Probability of j ships in the system:

$$\begin{aligned} P(j) &= P(0)\frac{\rho^j}{j!} && \text{for } j < n \\ &= P(0)\frac{\rho^n}{n!}\left(\frac{\rho}{n}\right)^{j-n} && \text{for } j \geq n \end{aligned}$$

Probability that an arriving ship has to wait before being served:

$$S_q = P(0)\frac{\rho^n}{n!}\frac{n}{n-\rho} = C(n,p)$$

in which $C(n,p)$ is called Erlang's C-formula.

Long-term average number of ships in the system:

$$L_s = P(0)\rho\sum_{j=0}^{n-2}\frac{\rho^j}{j!} + C(n,p)\left[n + \frac{\rho}{n-\rho}\right]$$

Long-term average number of ships in the queue.

$$L_q = C(n,p)\frac{\rho}{n-\rho}$$

Long-term average time in the system:

$$W_s = \frac{L_s}{\lambda}$$

Long-term average waiting time:

$$W_q = \frac{L_q}{\lambda} = C(n,\rho)\frac{1}{n\mu}\frac{n}{n-\rho}$$

Utilisation rate:

$$u = \frac{\rho}{n}$$

Example box 2.3: Design of a break bulk terminal

1. Case
We are to design a break bulk terminal.

Negative exponential distribution of interarrival times, with parameter λ.

Negative exponential distribution of service times, with parameter μ

Example box 2.3 – continued on next page

Example box 2.3 – continued from previous page

A working day consists of two 8-hour shifts. There are 6 working days per week, and 50 working weeks per year.

Cargo forecast: 600,000 ton/year

Average number of gangs (groups of dock workers) employed per ship: 2.5

Production per gang: 12.5 ton/hr

Max acceptable waiting time - 0.25 times average service time

2. Objectives
To determine:

- To determine the minimum number of berths required to meet the waiting time requirements, and
- the corresponding average berth occupancy.

3. Solution
Queueing system: M/M/n: ∞/∞/FIFO

Operational hours: 2 * 8 * 6 * 50 = 4800 hr/yr

Arrival rate per berth: λ = 600,000 ton/yr

Service rate per berth: μ = 150,000 ton/yr

$\rho = \lambda/\mu = 4$

Number of berths with 100% occupancy: 4 (starting value)

Waiting time infinite $\rightarrow$ increase number of berths to 5

M/M/n-table for $n = 5$ and occupancy 0.8: $W/S = 0.5541$ $\rightarrow$ increase number of berths to 6

M/M/n-table for $n = 6$ and occupancy 0.67: $W/S = 0.152$ $\rightarrow$ meets requirement

4. Conclusion
Minimum 6 berths required, with an occupancy of 67%

2.5 Numerical approximations of queueing systems

It is not possible (or practical) to derive analytical solutions for all queueing systems; many require a numerical approach. A typical way to do this is simulation: interarrival and service times per customer are drawn at random from the given probability distributions. The other factors characterising the queueing system, viz. the number of service points, the size of the calling population, the number of places in the system and the queue discipline, are handled deterministically in the simulation software. Each customer is run through the system and waiting and service times are recorded for statistical analysis.

Table 2.7 shows an example output for 10 customers of an M/M/1 queueing system, with 8 arrivals and 9 services per hour on average. The first column gives the customer's identifier, in this case its arrival serial number. The second and third columns list the drawn values of the interarrival time (IAT) and the service time (ST), both in seconds. Time starts at $t = 0$ with no customers in the system. Customer 1 arrives after IAT(1) seconds and, since there are no other customers in the system, he or she is served immediately. So the arrival time AT(1) is equal to IAT(1) and so is the time TSB(1) that service begins. This service ends ST(1) seconds later, so at time TSE(1) = TSB(1) + ST(1). This is the moment that Customer 1 leaves the system. The time TCSS(1) the customer spent

c	IAT	ST	AT	TSB	TSE	TCSS	TCWQ	ITS	QL
1	770.058680	327.407626	770.058680	770.058680	1097.466305	327.407625	0.000000	770.058680	1
2	205.326085	90.992827	975.384765	1097.466305	1188.459132	213.074367	122.081540	0.000000	1
3	200.282222	90.603747	1175.666986	1188.459132	1279.062879	103.395892	12.792145	0.000000	0
4	127.819803	182.644607	1303.486789	1303.486789	1486.131396	182.644607	0.000000	24.423911	1
5	83.275849	282.955522	1386.762638	1486.131396	1769.086918	382.324280	99.368758	0.000000	1
6	192.753662	149.813260	1579.516300	1769.086918	1918.900177	339.383878	189.570618	0.000000	0
7	635.795797	395.303652	2215.312096	2215.312096	2610.615748	395.303652	0.000000	296.411919	3
8	141.942446	17.955685	2357.254543	2610.615748	2628.571433	271.316890	253.361205	0.000000	2
9	159.547619	1314.952441	2516.802161	2628.571433	3943.523874	1426.721713	111.769272	0.000000	8
10	12.377204	114.134531	2529.179365	3943.523874	4057.658405	1528.479039	1414.344509	0.000000	8

Table 2.7: Example output of an M/M/1 queueing system simulation (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

in the system is the interval between TSE(1) and AT(1). Since the system time was said to start at 0, the server was idle until the first customer arrived, causing and idle time server ITS(1) = AT(1).

Before the service of Customer 1 has ended, Customer 2 arrives, so he/she has to wait in the queue until the service is available. This causes a queue length QL(1) of 1 during the presence of Customer 1 in the system. After departure of Customer 1 we follow the same steps for Customer 2 and all subsequent customers, thus filling in the table row by row. Once a sufficient number of customers has been dealt with, the simulation results can be analysed statistically, yielding quantities such as $P(0)$, $P(n)$, L_s, L_q, W_s and W_q.

A statistic that is often used in ports and waterways performance studies is the ratio of the long-term average of the waiting time over the long-term average of the service time:

$$\frac{\overline{TCWQ}}{\overline{ST}} \tag{2.39}$$

Each cell in Table 2.6, for example, is derived from $\overline{TCWQ}/\overline{ST}$ calculation on the output of a "M/M/n: ∞/∞/FIFO" calculation using $1 \cdot 10^6$ iterations. While more iterations do tend to lead to more stable results, it should be that the stochastic nature of the calculations means simulation results are not exactly identical. This is why tables found at various places in literature tend not to be exactly identical, unless they were generated with an analytical solution.

2.5.1 Application

In the example above, as well as in Part II – Chapter 4, we have seen how tables from queueing theory are applied in the design of a terminal, especially the determination of the required number of berths. But the operations on the terminal itself (supply, transport and storage of unloaded cargo, or collection, transport and pick-up of cargo to be loaded) are also supply chain processes with random components. Numerical simulations like the one shown in Table 2.7 can be useful to optimise these processes.

The examples also made clear how strongly the design is influenced by waiting time limitations and by the random character of the arrival and service processes. Waiting time limitations are usually based on economic arguments and/or competition with other ports. One may also try to influence the design, however, by service priority pricing (thus changing the queue discipline), or by traffic regulation (thus influencing the arrival statistics). The more vessels make long-planned roundtrips, the earlier and the better one may estimate arrival times at a port, thus enabling planning in advance of services.

Queueing also plays a role in inland waterways, especially near locks. Here, too, there is a random arrival process and a more or less random service process, which at least depends on the mix of vessels to be locked. The arrival process is not necessarily completely random, especially if there are other locks not far ahead in the same waterway. In that case, a narrow normal distribution is more suitable for the interarrival times than an M- or E_k-distribution.

For many years Rijkswaterstaat has used the Kooman method (Kooman and De Bruijn, 1975) to determine waiting and passage times at locks. It is partly based on empirical relationships (e.g. of the number of vessels that fit into a lock, given the average tonnage), partly on queueing theory. At the moment, this method is being replaced by computer simulations.

Locks are very common in waterways, natural or man-made. In rivers, weir and lock systems are used to make the river navigable, also at low water levels. An example is the river Maas, which in the Netherlands has seven weir/lock combinations (Figure 2.23).

Another example is the Main-Donau Kanal, which needs as many as 16 locks to negotiate the drainage divide between the Rhine-Main and Danube basins (Figure 2.24).

In such cases, the capacity of the waterway strongly depends on the capacity of the locks and the time spent sailing from one end to the other is dominated by the passage times of the locks. In Part III – Chapter 3 we have described how passage times and lock capacities can be determined. Note, however, that that capacity is not the only indicator of lock performance. Depending on the statistics of the interarrival time and the vessel mix in the lock, the maximum I/C ratio will be significantly smaller than 1, due to waiting time limitations (also see Figure 2.12).

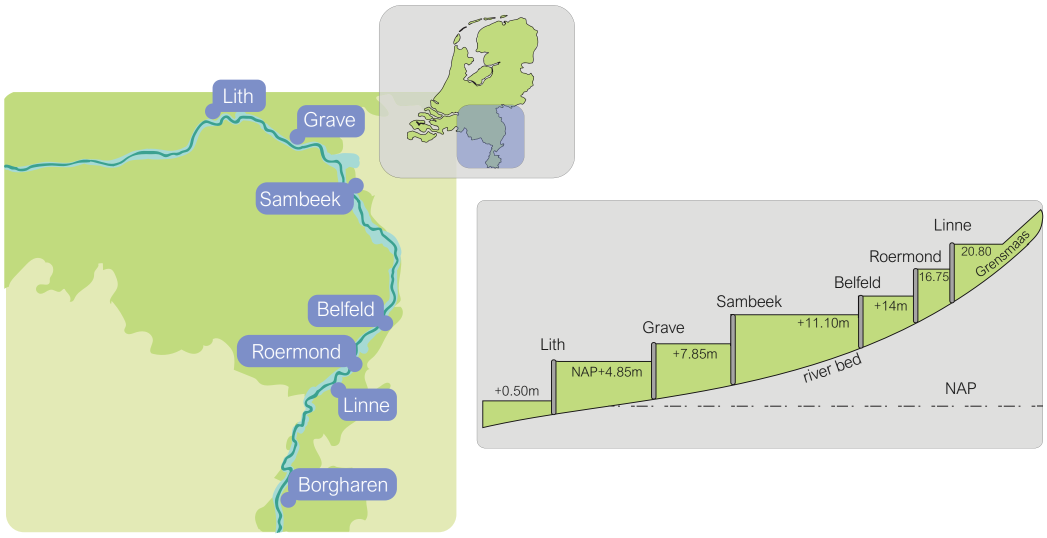


Figure 2.23: Weir/lock systems in the river Maas in the Netherlands (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

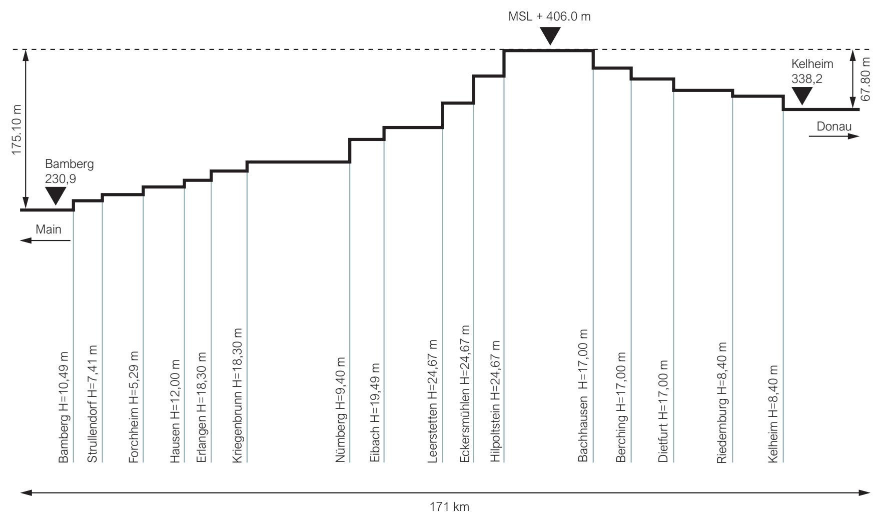


Figure 2.24: Locks in the Main-Donau Kanal (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

2.6 Simulation models

2.6.1 National simulation models

Governments typically use information as described in the previous sections to analyse (1) whether the system under their control is or will be having problems (now or in the near future), and (2) what measures are likely going to be most effective to mitigate these problems.

As an example case we describe the modelling landscape set up and maintained by the Dutch Ministry of Public Works, to support policy making related to the waterway network. A chain of interconnected models that range from a national scale and a time horizon of 15 – 30 years, to a more local scale and and a time scale of minutes (see Figure 2.25).

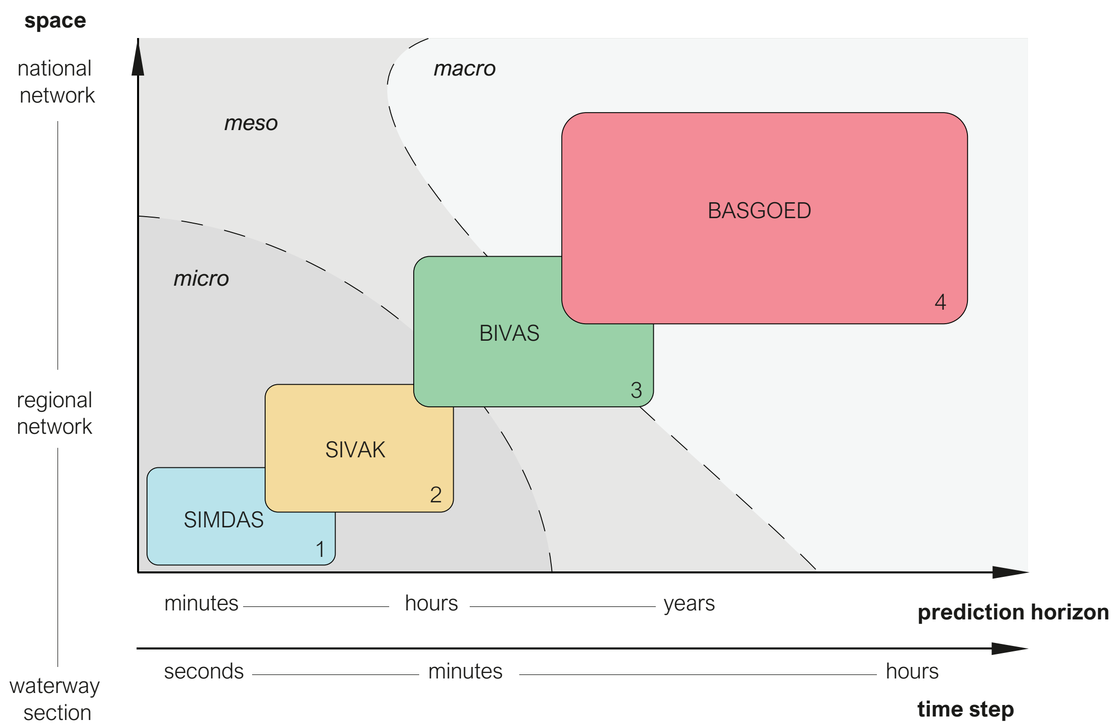


Figure 2.25: Waterways modelling landscape Rijkswaterstaat (modified from version by Tom van der Schelde, Rijkswaterstaat, by TU Delft – Ports and Waterways is licenced by CC BY-NC-SA 4.0).

BASGOED

BASGOED ('Basismodel voor Goederenvervoer') is the Netherlands' basic model to predict future transport of goods. Looking 15 – 30 years ahead, it estimates:

- the amount of goods that are produced and consumed,
- what part of this amount needs to be transported, and from which origin to which destination, and
- which transport modality will take care of what part of this transport demand.

BASGOED predicts the tons transported per cargo type and modality, on origin-destination pairs, based on sector-specific anticipated growth in combination with travel time and travel cost for the road, rail and IWT modalities.

For road transport the number of trips is also predicted. BASGOED provides crucial input for road transport: the National Model System (LMS) and the National Region Model (NRM); for rail transport: the Network Evaluation Model (NEMO); and for IWT: 'Binnenvaart Analyse Systeem' (BIVAS), 'Simulatiepakket voor Verkeersafwikkeling' (SIVAK) and 'Algemeen Scheepvaart Simulatiemodel' (SIMDAS).

BIVAS

BIVAS was developed to perform network analyses for IWT. The application provides support for answering policy-related questions on topics such as:

- traffic loads on waterways and infrastructure (locks, bridges),
- the effect of blockages in the network,
- the effect assessment of management strategies, and
- the effect assessment of maintenance scenarios.

Traffic flows are calculated based on the number of trips that need to be made on given origin-destination pairs (based on BASGOED). BIVAS checks if a trip can be made, and executes it as soon as it can. As a result BIVAS can predict the number of trips that make use of the network, but the individual trips are not simulated as such. Around key infrastructure, such as locks and bridges, the SIVAK model provides more detail. On waterway sections, in bends and on intersections, the SIMDAS model provides more detail.

SIVAK

SIVAK is a detailed simulation model for traffic flows near locks, bridges, waterway restrictions and combinations thereof. It allows for dynamic route selection and can calculate waiting times depending on arrival patterns and service rates.

Van Adrichem (2020) applied SIVAK as a benchmark, to investigate whether mathematical optimization of lock scheduling could significantly improve locking capacity.

SIMDAS

SIMDAS is a general shipping simulation model for waterway sections, bends and intersections. It can be used to calculate capacity and congestion effects on waterways. It resolves the position of vessels on the waterway and simulates interactions between vessels during encountering and overtaking manoeuvres. As such it complements SIVAK.

Verschuren (2020) investigated the effects of the low discharge extreme of 2018 on traffic flow on the river Waal. She used SIMDAS to investigate at which discharge levels the fairway would be so restricted that queue formation was likely to occur.

2.6.2 Research simulation models

The models described above have been developed with the clear purpose to support formal policy and decision making by Rijkswaterstaat and the Ministry of Public Works. Over the years much effort has gone into preparing and improving crucial inputs for the models, such as the careful specification of the waterway network (see also http://www.vaarweginformatie.nl) and the properties of the fleet. As a result, the modelling landscape forms the widely accepted platform that is commonly used to study the behaviour of the existing network and the effect of policies.

For new types of questions the robust quality of the modelling landscape can make the testing of new formulations and approaches a bit more cumbersome. Issues like calculating energy consumption and emissions on networks, or investigating the effect of low discharge extremes on the waterway capacity and fleet occupation, are typically easier investigated in more flexible systems. Once a new approach or formulation has been developed and properly tested, it may subsequently be implemented into the modelling landscape.

To facilitate the development of innovative approaches TU Delft developed a number of dedicated open source python packages that allow researchers to develop and test innovative approaches in a flexible and adaptable research environment.

We describe some of the more relevant packages here briefly.

OpenQTSim – Queueing Theory Simulation

For the numerical approximation of Kendall type queueing systems Van Koningsveld and Den Uijl (2020a) developed the python package OpenQTSim. It utilises the discrete event simulation and queue handling capabilities of the SimPy package, and the statistical functionality available in the SciPy package. Combined, this enables simulation of queueing system behaviour that emerges from inter-arrival and service times that follow predefined statistical distributions (see also Section 2.5).

The tool has been used to develop the waiting time as a function of service time tables presented in Part II – Table 3.9 and Table 3.10 and Table 2.6 in this chapter. Since generating these tables involves large amounts of simulations, OpenQTSim includes a multi-thread engine which allows the calculations to be run on multiple cores in parallel. The setup with SimPy furthermore enables the integration of additional restrictions that are normally not part of queueing simulators, such as limitations by available quay lengths, tidal windows and fairway restrictions.

OpenTNSim – Transport Network Simulation

Many studies of waterway systems aim to quantify traffic flows over the network, and the effects of interventions in the system. For safety studies detailed information about manoeuvring and ship-ship interactions may be needed, but for most capacity-related studies, as well as environmental effect studies, meso-scale traffic flows over the network are sufficient.

Apart from the national landscape of simulation models, numerous commercial packages are available to study the behaviour of agents on a network. Because for research purposes, policy-support and commercial software do not always provide the most flexible environment to test new algorithms, Van Koningsveld and Den Uijl (2020b) developed the OpenTNSim package.

OpenTNSim is a Python package for the investigation of meso-scopic traffic behaviour on networks to compare the consequences of different traffic scenarios and network configurations. The meso-scopic level (see also Figure 2.25) is of particular interest to problems that simultaneously require a large study area *and* more detailed engineering models to quantify specific aspects of the network or of the agents using it. Examples are the effects of network restrictions on traffic flows (e.g. due to maintenance, incidents, changing water levels), or of the assessment of the (environmental) cost and benefits of policy measures.

OpenTNSim uses the NetworkX package for transport graph construction and route selection. To investigate traffic flows and queueing patterns the discrete event simulation package SimPy is used. The Geospatial Data Abstraction Library (GDAL) is used to handle geospatial projections and operations. OpenTNSim contains a library that facilitates flexible specification of agents and various tools that facilitate the analysis of network behaviour.

Since OpenTNSim is built on widely used packages and libraries, it is quite robust and powerful. To facilitate use an automatic coupling is made to the Dutch Fairways Information Services (FIS), which is made available via http://www.waarweginformatie.nl. Fairway properties are automatically added to a graph, which subsequently can be used for routing questions and simulations. Interfaces are furthermore available to couple traffic simulations with the output of hydrodynamic models such as SOBEK (1D) or Delft3D (2DH).

Van der Does de Willebois (2019) used OpenTNSim to investigate the potential impact of quaywall maintenance on traffic flows over the canals of the city of Amsterdam. For this he characterised and implemented the behaviour of three types of agents that showed distinctly different behaviour. Groen (2020) expanded on this work looking at the impact of lock maintenance on the larger IWT network. For this he generated origin-destination information from AIS data. Vehmeijer (2019) used OpenTNSim to estimate CO_2 emission footprints of IWT traffic on on the Rotterdam – Antwerp corridor. For this she implemented simplified resistance estimation algorithms in combination with route selection algorithms to investigate the effect of policy measures and network modifications. Segers (2021) updated the resistance estimation algorithms based on new available literature, and added routines to estimate other emissions, such as SO_x, NO_x and fine dust. Kok (2021) expanded on this work by adding a fuel use estimator in order to develop a method to design suitable bunkering locations in case alternative energy carriers are used in IWT.

OpenCLSim – Complex Logistics Simulation

Apart from the performance of transport corridors, another category of interesting problems is the performance of (complex) waterborne supply chains. Where OpenTNSim focuses on network performance for a given traffic load, OpenCLSim aims to quantify the behaviour that follows from rule-based planning of (interdependent) cyclic activities, such as marine construction processes where one activity depends on the completion of another *and* each activity has its own sensitivity to currents and waves. To assess the complex behaviour of such interdependent supply chains we need to be able to simulate the behaviour of cyclic activities that are subject to logical rules. Examples are:

- the installation of an offshore wind park where first the monopiles have to be placed, before the wind turbine generators can be mounted,
- the construction of a submerged tunnel, where first a trench needs to be dug, before the prefabricated tunnel elements can be lowered into place,
- the realisation of a land reclamation, where first sand needs to be supplied until a sufficiently large area of land above water is created, before dry earth moving equipment can be mobilised to assist in the above water profiling,
- the execution of a dike reinforcement, where first base and filter layers need to be installed, before the toplayer of large rock can be installed,
- the supply of containers to a hinterland, where containers are first delivered to a sea port by very large ocean-going vessels, before a fleet of smaller inland container vessels can transport them to a series of inland ports.

The interdependence of activities in port and waterway settings generally translates into decisions on when to mobilise a vessel to avoid unnecessary (and typically expensive) waiting times, on how large certain storage facilities need to be to ensure that disruptions in one supply chain don't affect the others, et cetera. The interdependence of supply chains is already challenging, but it becomes even more complex and interesting when environmental and human restrictions play a role.

Van Koningsveld et al. (2021) developed OpenCLSim to study challenges like the ones mentioned above. Den Uijl (2018) investigated the potential of integrating engineering knowledge in logistical simulation of dredging projects. He showed in particular how application of suspended sediment spill restrictions would affect the overall project planning of dredging projects. Van der Bilt (2019) elaborated on this by implementing routines to estimate the power required during dredging operations, and subsequently the associated emissions. By analysing the execution of the same project, while using alternative execution methods, it becomes possible to compare the impact of alternative work methods. Kievits (2019) and Vinke et al. (2019, 2022) showed how the occurance of low discharge extremes affects not only the performance of key supply chains, but also impacts the overall fleet utilisation and ultimately the overall transport capacity of the system. They used the 1D hydrodynamics model SOBEK to translate discharge variations to water depths along the river. By subsequently translating available waterdepth into loading capacities, the impact of reduced water levels on the overall supply chain can be simulated. Van Halem (2019) expanded on this combination of OpenCLSim with a 1D flow model, by looking at the impact of time-varying 2DH flowfields. He showed that in open water with larger-scale currents, like in estuaries and coastal seas, the shortest route is not always the fastest. He furthermore demonstrated that in case of larger tidal motions and a complex bathymetry, it may even be beneficial to take on less cargo, when the reduced draught opens up a significantly shorter transport route.

OpenTISim – Terminal Investment Simulation

Where OpenTNSim and OpenCLSim are focused on waterways and logistics, the OpenTISim package (Van Koningsveld, 2020a) focuses on terminal development. In Part II – Chapter 3, 4 and 5 the design of terminals as a function of the desired annual throughput is discussed. Especially in functional designs, numerous trade-offs can and need to be investigated. The python package OpenTISim incorporates a range of design rules and investment triggers, for dry bulk, liquid bulk and container terminals, in order to investigate the impact of certain design choices on the overall business case of the terminal. Based on an anticipated development in demand, the model parametrically triggers additional investments in berths, quays, cranes, storage and hinterland facilities. By keeping track of the costs associated with each added terminal element, the overall cashflows in terms of CAPital EXpenditures (CAPEX), OPerational EXpenditures (OPEX) and revenues can be derived.

Ijzermans (2019) applied OpenTISim to agribulk terminals. Where typically the available design guidelines provide suggested service levels, in terms of a maximum allowable waiting time as a factor service time, he explored the effect of 'playing' with this factor on the overall businesscase of the terminal in terms of NPV. It turned out that longer waiting times were often defensible, at least in terms of NPV of the overall project. Lanphen (2019) developed a liquid bulk module for OpenTISim to investigate the aspects involved in developing an import terminal for hydrogen. First, an analysis was made as to what hydrogen carrier would be preferential as a function of transport distance. Second, a functional design of hydrogen import terminals for four different energy carriers was made to illustrate which terminal elements were most critical in terms of the overall business case. Koster (2019) developed a container terminal module to analyse the effect of different yard equipment on the overall land requirements.

Stam (2020) combined OpenTISim with OpenCLSim to investigate trade-offs in port systems; i.e. the combination of an onshore port with an offshore port, connected by a barge link or a causeway. Through this combination it could be investigated, for example, how wave- related downtime of the barge link would affect the storage requirements in the offshore port, given the effect that such downtimes would have on dwell times. Abrahamse (2021) used a similar combination of OpenTISim and OpenCLSim to investigate the effects of alternative supply chain configurations on the cost of hydrogen at the end-use location.

In the next chapters we briefly illustrate typical port and waterway performance challenges as they may be encountered when looking at ports and terminals (Chapter 3), waterways and port water areas (Chapter 4) and port and waterway systems (Chapter 5).

3 Ports and terminals

This chapter illustrates some typical performance trade-offs that may be encountered in ports.

3.1 Terminal design alternatives and space

3.1.1 Selection of container terminal equipment

The selection of container terminal equipment is the first and one of the most important steps in container terminal design. A selection needs to be made of:

- Quay-side equipment
- Transfer equipment, from the quay side to the yard, and
- Yard equipment

Which options are preferred depends primarily on the following criteria:

- Container terminal throughput
- Terminal efficiency
- Costs

For a container terminal operator to be competitive, costs per container (USD/TEU) should remain as low as possible, while sufficient service needs to be provided to the container owner in terms of terminal efficiency and throughput capacity. This requires careful trade-offs when deciding on preferred terminal equipment.

One can imagine that a terminal on a small island with one vessel visit per week would not require highly automated expensive equipment which is able to offload the vessel quickly, yet subsequently would stand idle. For a large and busy port, such as the Port of Rotterdam, containers need to be offloaded as quickly as possible, against low costs, such that the shipping lines can continue as quickly as possible to their following destination.

The choice of the container terminal handling system depends on quite some factors, each having an impact on costs, efficiency and terminal throughput (see PIANC, 2014d):

- Vessel size
- Traffic forecast (TEU/year)
- Container volume in peak hours
- Available land area
- Required stacking density of the containers (configuration of stacking yard)
- Costs
- Target Ship-To-Shore (STS) productivity (moves/hr)
- Geographic restrictions of the terminal area
- Contingent restrictions due to soil conditions
- Environmental factors such as wind, ice, noise, light and snow
- Mean dwell time of containers in the stacking yard
- TEU ratio
- Percentage of reefer, empty, Out Of Gauge (OOG) and Less than Container Load (LCL) containers
- Connections to the hinterland transport modes, road, railway or IWT
- Expandability and flexibility
- Local or regional experience
- Availability of (skilled) labour

The selections of quay-side equipment, terminal equipment and transfer equipment are related to each other. An overview of feasible transfer and terminal equipment for each type of quay-side equipment is presented in

Figure 3.1, where:

- Mobile Harbour Crane (MHC)
- Ship-To-Shore (STS) crane
- Rubber Tyred Gantry (RTG) crane
- Rail Mounted Gantry (RMG) crane
- Tractor-Trailer (TT) system
- Straddle Carrier (SC)
- Reach Stacker (RS)
- Shuttle Carrier (ShC)

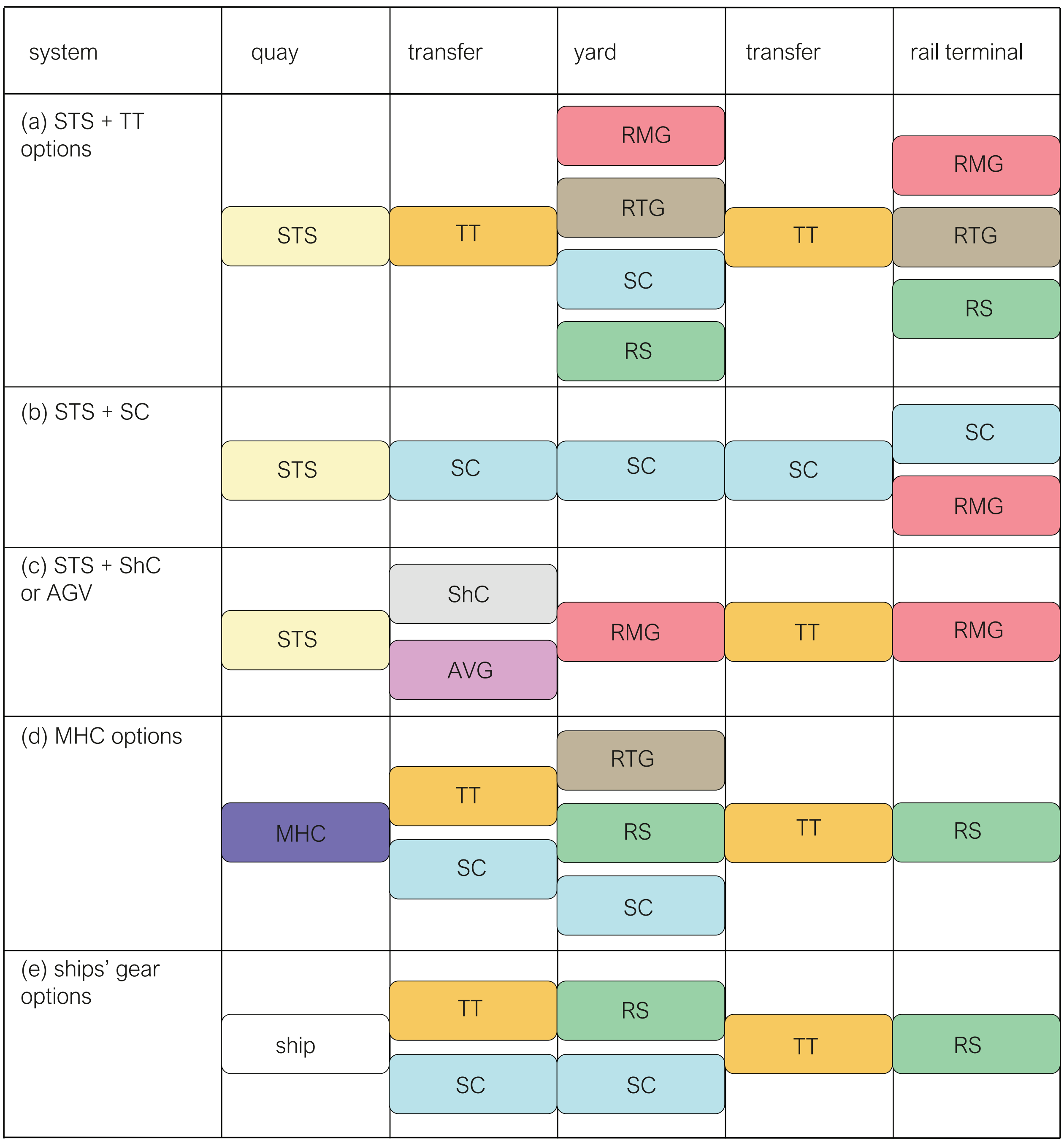


Figure 3.1: Overview of equipment types per quayside crane (reworked from PIANC, 2014d, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

There are three main types of quay side equipment (see Table 3.1 for advantages of the different types):

- Rail Mounted Quay Crane (RMQC) or STS crane
- Mobile Harbour Crane (MHC)
- Ship's gear

Topic	**Rail-Mounted Quay Gantry Crane (RMQC) or STS crane**	**Mobile Harbour Crane (MHC)**	**Ship's Gear**
Unit productivity	High; can be increased and operation decoupled from quay-to-stack transfers using double trolley cranes	Medium	Low; not affected by conflicting demands for cranes to serve other berths
Spacing along quay	Adjacent cranes can operate buffer-to-buffer, enabling high density coverage and berth productivity	Adjacent cranes must be well apart to avoid risk of colliding booms	Not applicable
Accessibility along vessel	Cranes can be readily moved along the quay for access throughout the vessel	Crane can cover several rows of containers along the vessel from a single position, then has to be moved	Not applicable
Associated horizontal transfer systems	Can be used with all types of horizontal transfer equipment	Suitable for use with tractor-trailers, and with SCs (straddle carriers) if the two operations are co-ordinated	Suitable for use with tractor- trailers in conjunction with mobile loaders (e.g. RSs reach stackers)
Loadings	High loadings on the rails may be reduced by adjusting the wheel configuration	Loadings on quay structure are distributed via the crane outriggers, designed to suit the quay loading capacity	Avoids the need for heavy foundations to support quay cranes
Power source	Usually employ shore electrical HV power supply, but diesel alternative exists	Usually diesel engine, avoiding the need for HV power supply, but may use shore electrical power if available	Zero energy cost to the terminal for ship-to-shore moves
Commissioning	Cranes usually delivered erected but require several weeks to commission	Fairly short delivery periods for rapid start-up, and cranes can be delivered at a location outside the terminal and can be hired for short periods	Lack of quay cranes avoids problems with delivery lead times and the reception and commissioning of equipment
Capital cost of cranes and supporting infrastructure	Highest	Medium	No investment required for quay cranes
Ability to handle other cargo	Cranes may be used to handle other types of cargo	Cranes may be used to handle other types of cargo	May be used to handle other types of cargo

Table 3.1: Advantages of each type of ship-to-shore operation (PIANC, 2014d).

The majority of container terminals, including small and medium sized terminals, operate with RMQCs. These cranes offer the highest productivity at the quay side for handling of containers, especially as several cranes can operate in close proximity. However, it is possible for smaller and medium-sized terminals to use other cranes due to cost considerations or other requirements. Mobile Harbour Cranes (MHCs) may be particularly appropriate in offering flexibility at multi-purpose terminals that handle general cargo as well as containers, whereas using ship's gear occasionally happens in very small terminals where older container vessels call. Where old general cargo terminals are converted into containers terminals, crane beams may not be present and hence MHCs would provide a useful alternative. When comparing the cost of different systems, the capital, operating and maintenance costs during the life of the facility should be considered.

3.1.2 Case example: yard equipment selection and surface area requirements

Sharif Mohseni (2014) presents a case comparison for identical quay side throughput for an STS crane and an MHC operation (see also Figure 3.2).

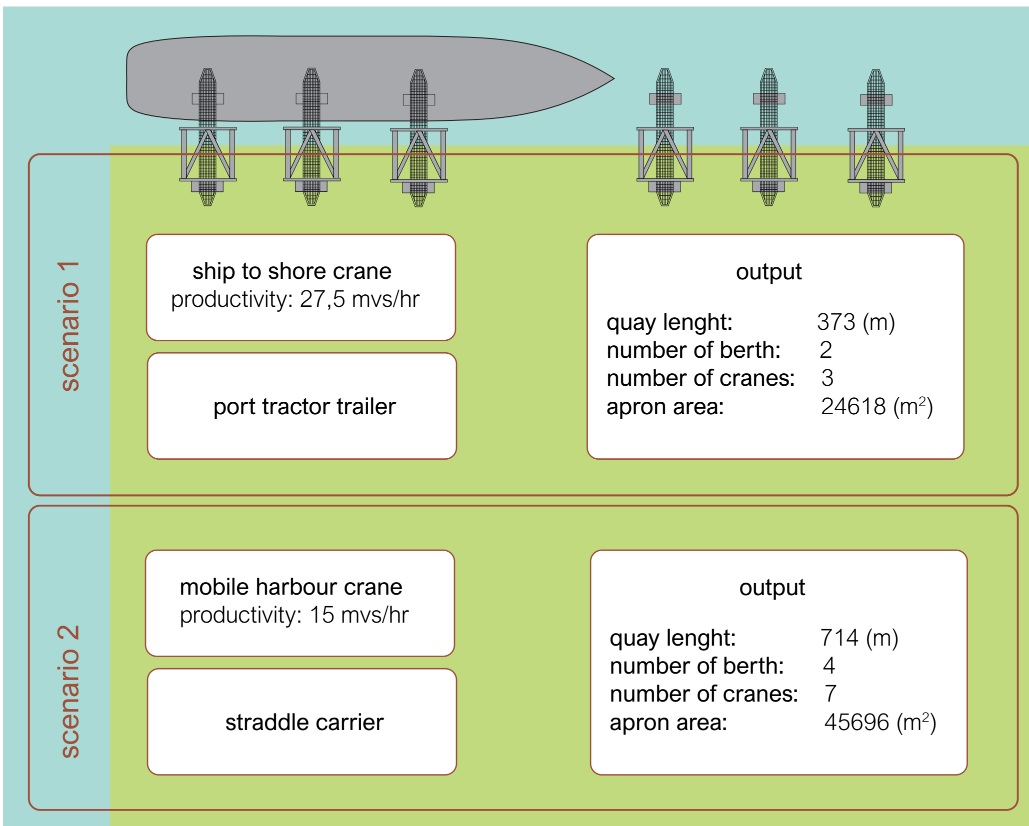


Figure 3.2: Key values for the two case scenarios (reworked from Sharif Mohseni, 2014, by TU Delft – Ports and Waterways is licenced by CC BY-NC-SA 4.0).

For cases with identical quay-side throughput, the selection of yard equipment determines to a large extent the overall layout of the container terminal (see also Part II – Chapter 4). Different types of yard equipment, are each associated with a particular placement of containers in the stacks. SCs, for example, require space between individual rows of containers (in lengthwise direction) to enable manoeuvring. Since RMGs can move over a few rows of containers at once, the containers in an RMG stack can be positioned closer together and thus require less space. The efficiency and stacking density determine to a great extent the number of ground slots that are needed. This in turn accounts to a large extent for the total surface area that a terminal requires. Office buildings, the workshop for repair and maintenance of the equipment, parking spaces, et cetera, also request additional space. Table 3.2 describes advantages of the main types of yard equipment. Figure 3.3 presents the calculated required yard area for various type of equipment as presented by Sharif Mohseni (2014). The amount of equipment and its utilization (hrs/year) determines the required investment cost (CAPEX) and yearly operating costs (OPEX) of equipment.

Topic	Rail-Mounted Quay Gantry Crane (RMQC)	Rubber Tired Gantry (RTG) crane	Straddle Carrier (SC)	Mobile (e.g. Reach Stacker (RS), ECH)
Stacking density	Potential for high speeds, stacking densities and precision	Potential for high stacking densities	Potential for medium stacking densities and good accessibility to containers	Potential for high stacking densities for empty containers
Stack width and height	Can be designed for a wide range of spans and stack heights	Can be designed to span up to 9 rows and up to 6 tiers high	Can be designed to stack 4 tiers high	Can be designed to stack full containers up to 5 tiers high (in first row) and to block stack empty containers 8 tiers high
Terminal shape	Limited to terminals with large rectangular stacking areas	Suited to terminals with large rectangular stacking areas	Can operate in irregularly shaped stacking areas	Can operate in irregularly shaped stacking areas
Paving require-ments	Paving of stack areas can be lighter duty if heavy vehicles are excluded	Paving of stack areas can be lighter duty if heavy vehicles are excluded	Entire stack yard generally has to accommodate the heaviest loadings	Entire stack yard generally has to accommodate the heaviest loadings
Power source	Usually employ fixed HV electrical power supply, but diesel alternative exists if power supply is inadequate	Usually powered by crane's diesel engine, avoiding the need for HV power supply, but fixed electrical power is also available for low emissions	No requirement for electrical power supply infrastructure	No requirement for electrical power supply infrastructure
Emissions	Zero air and low noise emissions with electrical power	Medium air and noise emissions with diesel power, low or zero with electrical power	Medium air and noise emissions	Medium air and noise emissions
Delivery lead time	Long lead time	Long lead time	Medium lead time	Short delivery lead time and low technology facilitate rapid start-up with minimal training
Capital costs	High, but long design life and low maintenance should help to minimise whole-life costs	Medium	Medium to low, but total fleet cost may be comparable to RTG system; relatively high maintenance costs for equipment and pavement	Relatively low, suitable for low budget terminals; relatively high pavement maintenance costs

Table 3.2: Advantages of various types of yard equipment (PIANC, 2014d).

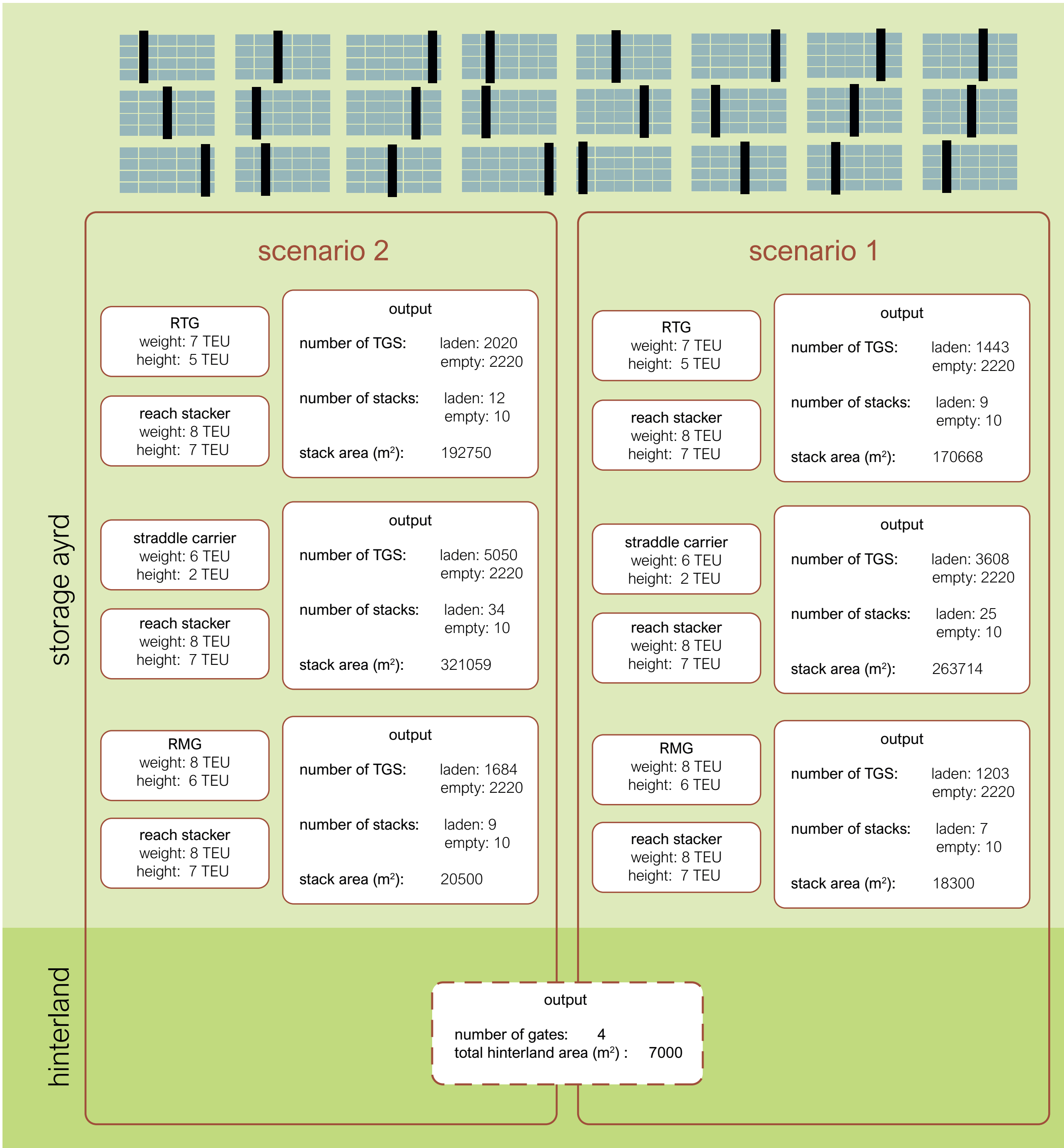


Figure 3.3: Overview of results for the two case scenarios (reworked from Sharif Mohseni, 2014, by TU Delft – Ports and Waterways is licenced by CC BY-NC-SA 4.0).

It is interesting to note that in both scenarios, selecting SCs as preferred yard equipment leads to approximately 50% larger stack area space requirements, than in the cases were RTGs or RMGs are selected. While there are some clear advantages for SCs as preferred yard equipment, mainly in terms of space required, other factors also play a role in the ultimate decision process. Associated cost might be important as well, as are the local conditions (availability and cost of land, availability of skilled labour, energy prices, et cetera).

Apart from yard equipment, the selection of appropriate transfer equipment is important. Table 3.3 lists advantages of various types of transfer equipement.

Topic	Tractor-Trailer	Straddle Carrier	AGV
Manoeuvrability	High	High, but should be restricted for safety reasons; can travel between the RMQC rails if there is sufficient headroom, otherwise under the back reach	Limited to designated paths
Interface with Ship-to-Shore operations	Quay crane depends on presence of correctly positioned tractor-trailer	Ability to lift and travel with load enables transfer operations to be decoupled from ship-to-shore operations, but SC must deposit outbound containers accurately on the quay	Types that can also lift containers enable transfer operations to be decoupled from quay operations; for others, quay crane depends on presence of AGV
Interface with stacking operations	Stacking crane depends on presence of correctly positioned tractor-trailer	SC is also used for stacking operations, so no other equipment is required and there are no stacking interface problems; SCs serving end-on RMG stacks must deposit inbound containers accurately	Types that can also lift containers enable transfer operations to be decoupled from stack operations; for others, stacking crane depends on presence of AGV
Quay apron requirements	Very wide quay aprons can be avoided, and narrow traffic lanes can be used	Very wide quay aprons can be avoided unless the SCs are automated	Very wide quay aprons are required
Compatibility with automation	Can be integrated with automated stacking systems	Can be automated and can be integrated with automated stacking systems	An essential element of a fully automated terminal, enhancing personnel safety
Positioning	No infrastructure required for guidance/positioning, but may be deployed at quay and yard cranes to enhance interfaces	No infrastructure required for guidance/positioning, except for automated SCs, but may be deployed to enhance interfaces with quay and yard cranes	AGVs facilitate precise positioning at both ends of cycle
Wheel loadings	Lowest	Medium	Highest, depending on type
Emissions	Low emission diesel engines are available	Low emission diesel engines are available	Low emission diesel engines are available; future use of battery power would suit low/zero-emission terminals
Capital cost	Lowest	Medium/high, but extensive heavy-duty paving also required	Medium/high, but extensive heavy duty paving also required

Table 3.3 – Continued on next page

Table 3.3 – continued from previous page

Risk of accidents	Medium accident risk for drivers	High accident risk for drivers	Normally no accident risks for persons as they are not allowed in automated operation areas
Driver require-ments	Short delivery lead times and low technology facilitate rapid start-up with minimal training	Drivers need special training; with direct operations, numbers are relatively low	No drivers required
Mainten-ance facility require-ments	Basic; the facility to separate tractors and trailers provides further operational flexibility	Usually require specially designed high- bay workshops and facilities for cleaning and access	High standard; also highly trained maintenance staff are required
Potential for redeploy-ment	Can readily be redeployed between terminals	Normal road transport impossible	Can be readily redeployed between similarly equipped terminals; normal road transport on trailers possible

Table 3.3: Advantages of various types of transfer equipment (PIANC, 2014d).

3.1.3 Summary of alternatives

Container terminal operations are a highly competitive business. The choice of quayside equipment, transfer equipment and storage yard equipment will be based on a trade-off between costs, efficiency and reliability. Costs play a major role in this trade-off and therefore terminal operations are selected which provide the lowest USD/TEU for the costumer, whilst offering sufficiently efficient and reliable operations. Cost items of container yard operations which would typically be considered are:

- CAPital EXpenditures (CAPEX)
  - Equipment
  - Yard monitoring & evaluation and drainage systems
  - Pavement and soil improvements
  - Berth length
  - Buildings, incl. gates
  - IT, security and communication systems
- OPerational EXpenditures (OPEX)
  - Energy consumption (fuel, electricity)
  - Overhead
  - Repairs & maintenance
  - Replacements
  - Labour
  - Insurance

A simplified calculation example of two types of quay side equipment for two throughput scenarios is presented in Table 3.4. For explanatory purposes, the annual costs resulting from CAPEX (e.g. depreciation and interest) are expressed in USD/TEU to compare with OPEX. The example uses various cost figures as input, but actual numbers can greatly vary, based on local conditions or requirements. Also, any costs as a result of longer berth time for vessels is not considered in this calculation. It is important to note that the values presented in this case example are primarily intended as an illustration of the *principles* of the effects of equipment selection. They should *not* be used as a reference!

From Table 3.4 it can be seen that for small throughputs, investing in two more expensive STS cranes, is not paid back by lower annual operating costs. For larger throughputs, however the operating costs of using STS cranes are paid back by higher productivity per meter quay length and in OPEX per box move. The calculations should also be done for the yard operations and for the operations to transfer containers to the hinterland.

Other considerations for the trade-off include:

- In the low throughput scenario, the duration for offloading a vessel using an MHC would be much longer than using the STS cranes. Whether the longer berth time is acceptable to shipping lines and whether this would lead to other costs not presented in this example, would have to be considered.
- It can be considered that the low-throughput scenario is applicable to a first phase, while in time throughput will increase and the high scenario will be considered. In such a situation it may be wise to choose for the STS crane option from the start.
- MHCs can be used for offloading of break bulk or bulk. Hence, if the quay will be utilized for other purposes than solely containers, costs of the infrastructure and equipment can be distributed over more operations.

	Throughput	500,000	500,000	100,000	100,000
	Quay side				
		MHC	STS	MHC	STS
	TEU/crane/year	50000	160000	50000	160000
	Nr. cranes*	10	4	2	2
	Capex/crane	$ 3,500,000	8,000,000.0	$ 3,500,000	8,000,000.0
	Total CapEx	$ 35,000,000	$ 32,000,000	$ 7,000,000	$ 16,000,000
	Lifetime	15	15	15	15
	Discount rate	10%	10%	10%	10%
	USD/crane/yr	$ 418,326	$ 956,173	$ 418,326	$ 956,173
A	USD/yr	$ 4,183,257	$ 3,824,692	$ 836,651	$ 1,912,346
	TEU/m/year	500	1500	500	1500
	Berth Length**	1000	333.3	200	*200*
	Berth costs/m	$ 80,000	$ 80,000	$ 80,000	$ 80,000
	Berth costs	$ 80,000,000	$ 26,666,667	$ 16,000,000	$ 16,000,000
	Lifetime	50	50	50	50
	Discount rate	10%	10%	10%	10%
B	USD/yr	$ 7,335,213	$ 2,445,071	$ 1,467,043	$ 1,467,043
	Total quayside USD/yr (A+B)	$ 11,518,469	$ 6,269,763	$ 2,303,694	$ 3,379,388
1	Total CapEx USD/TEU	$ 23	$ 13	$ 23	$ 34
	TEU factor	1.6	1.6	1.6	1.6
	Moves per year	312,500	312,500	62,500	62,500
	kWh / move	N/A	6.5	N/A	6.5
	Liter / move	3.5	N/A	3.5	N/A
	USD/kWh	$ 0.25	$ 0.25	$ 0.25	$ 0.25
	USD/l	$ 1.00	$ 1.00	$ 1.00	$ 1.00
	Energy costs (USD/yr)	1,093,750	507,813	218,750	101,563
2	Energy costs / TEU	$ 2	$ 1	$ 2	$ 1
	Maintenance cranes (%CapEx/yr)	2%	2%	2%	2%
	Maintenance costs (USD/yr)	700,000	640,000	140,000	320,000
3	USD/TEU	1.40	1.28	1.40	3.20
	Total Costs Quayside USD/TEU 1+2+3	$ 27	$ 15	$ 27	$ 38

Table 3.4: Overview of cost estimates for the two case scenarios (Sharif Mohseni, 2014).

3.2 Terminal design alternatives and time

3.2.1 Will it pay off to design for future use?

Another trade-off question that often arises during the design of a new terminal, is whether it is wise to invest in more robust infrastructure, anticipating future savings. An example is investing in a more robust/future-proof quay wall, that is designed for higher (surcharge) loads and/or larger retaining heights than initially required.

This allows for example for future deepening in front of the quay wall when the terminal operator wants to service deeper-draught vessels. Or the quay wall can be used to tranship heavier cargo when a new client wants to use the existing infrastructure.

The robust/future-proof quay wall will be more expensive to construct (i.e. higher initial CAPEX) than a 'fit for purpose' quay wall. The owner of the quay wall will only invest in a more expensive structure when the business-case for the future proof quay wall, is better than for the 'fit for purpose' quay wall.

The next section discusses a case example to illustrate the effects of higher initial CAPEX of a future-proof quay wall on the business case of a terminal for several scenarios. NB: The case example is fictional and the values in this case illustrate the *principle* of a financial feasibility assessment only. They should *not* be used as a reference!

3.2.2 Case example: fit for purpose vs future-proof quay wall alternatives

In this case example, a landlord port authority has two main ways of generating income: (1) leasing out terminal areas with maritime infrastructure, and (2) collecting port dues for the vessels that arrive in the port. The port uses part of the port dues and the lease fees to cover its CAPEX and OPEX for the maritime infrastructure. The maritime infrastructure consists of a quay wall and the associated harbour basin.

The base case

The base case is the situation in which the port authority has a new client for a terminal area and the maritime infrastructure is designed for this specific client to provide a 'fit for purpose' solution at the lowest cost level. The new client wants to lease the terminal and maritime infrastructure for a period of 20 years. The quay wall has a technical life span of 40 years. The port authority makes a business case based on the expected CAPEX, OPEX and revenues, and determines the NPV of the cash flows using its standard discount rate (see also Part I – Section 2.2.4). Figure 3.4 shows the cash flows on the left-hand y-axis and the NPV on the right-hand y-axis.

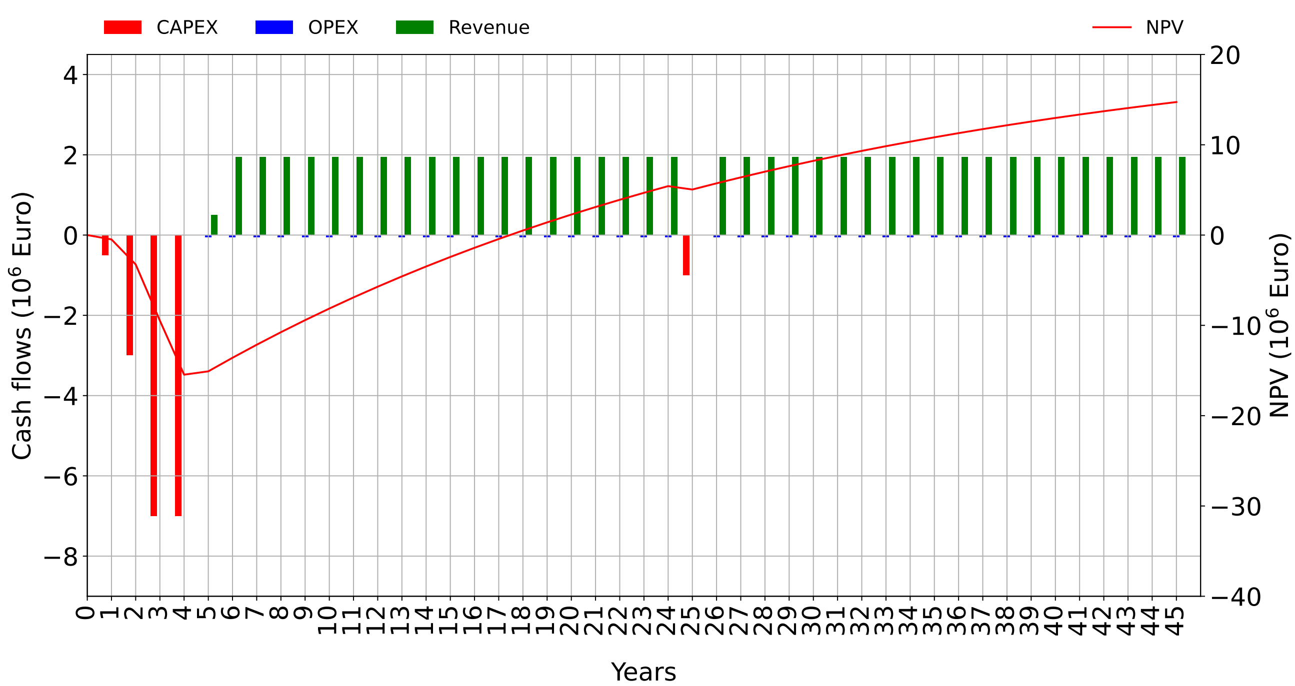


Figure 3.4: NPV calculation 'Base case' (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

It is assumed that the quay wall design phase and the construction phase take 4 years combined. After an operational time of 20 years, major maintenance is planned. The NPV shows that the quay wall is financially feasible after 18 years. Assuming the new client will continue their lease of the terminal area with the maritime infrastructure for another 20 years, the final NPV after 45 years amounts to 14.7 M€.

Two 'future-proof' alternatives

Future developments could set different requirements for the maritime infrastructure. The vessel sizes may increase in the future, demanding a larger depth in front of the quay wall; furthermore larger (especially wider) vessels require larger and heavier cranes. This will increase the vertical loads on the quay wall. That is why the port authority also investigates what happens when the client wants to serve larger vessels after a period of 20 years. Two alternatives are considered:

F-1. Construct a 'new quay at a different location' The first alternative is to construct a new quay wall at a different location while the 'fit for purpose' quay wall is rendered obsolete. The port authority has to invest in new infrastructure and is left with infrastructure that is tailored to the previous requirements of a specific client. It could prove to be difficult to find a new client for the old quay wall. For now, it is assumed that the port authority can find a new client within 2 years and that the lease fees for the old quay wall are lower than they were for the initial client. Figure 3.5 presents the cash flow and the NPV for the situation in which the port authority has to construct a new quay wall and find a new client for the original quay wall. NPV becomes positive after 18 years and after 29 years. Final NPV after 45 years is 14.0 M€.

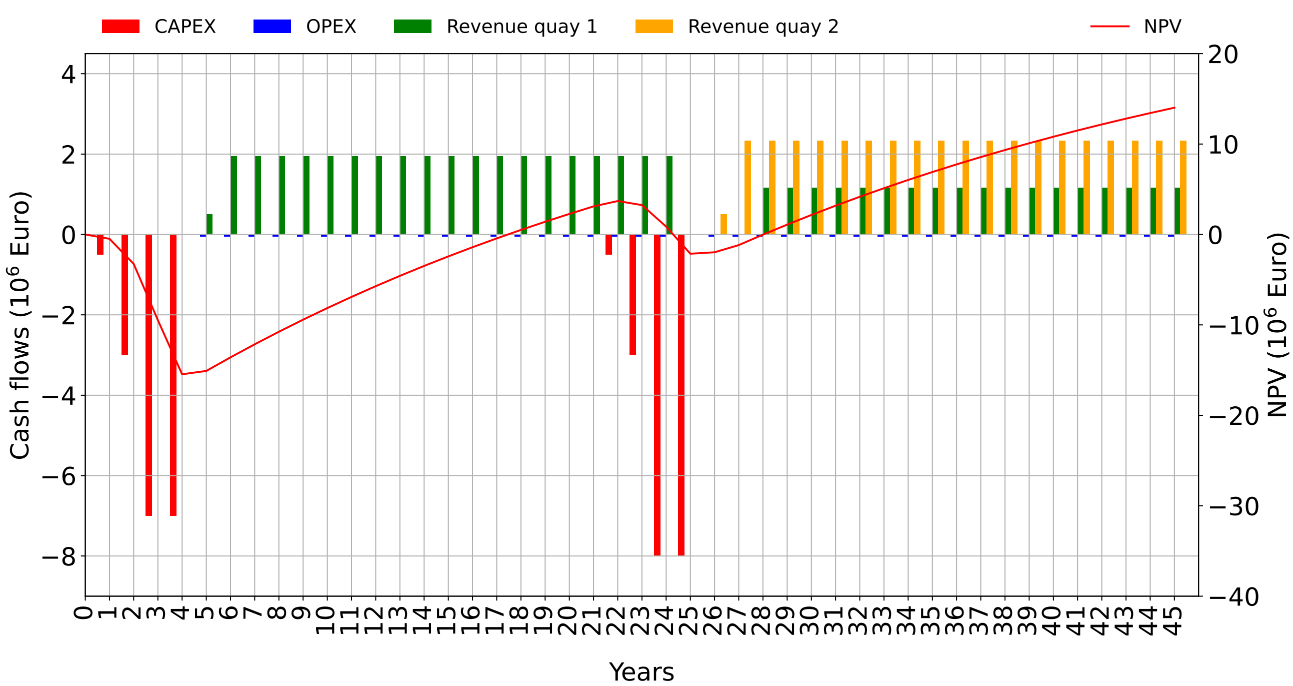


Figure 3.5: NPV calculation Scenario F-1 – 'new quay at a different location' (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

It should be noted that Figure 3.5 contains the cash flow and NPV for both the new and the original quay wall. The graph for the original quay wall should be used for a fair comparison between both alternatives (see Figure 3.6). It turns out that for that case the NPV is positive after 18 years and the final NPV is 10.3 M€.

F-2. Construct a future-proof, robust quay wall The second alternative is to design a future-proof, robust quay wall. This means that the initial investments are higher since the quay is designed for larger loads and larger retaining heights compared to the 'fit for purpose' quay wall. Will this investment in future use pay off?

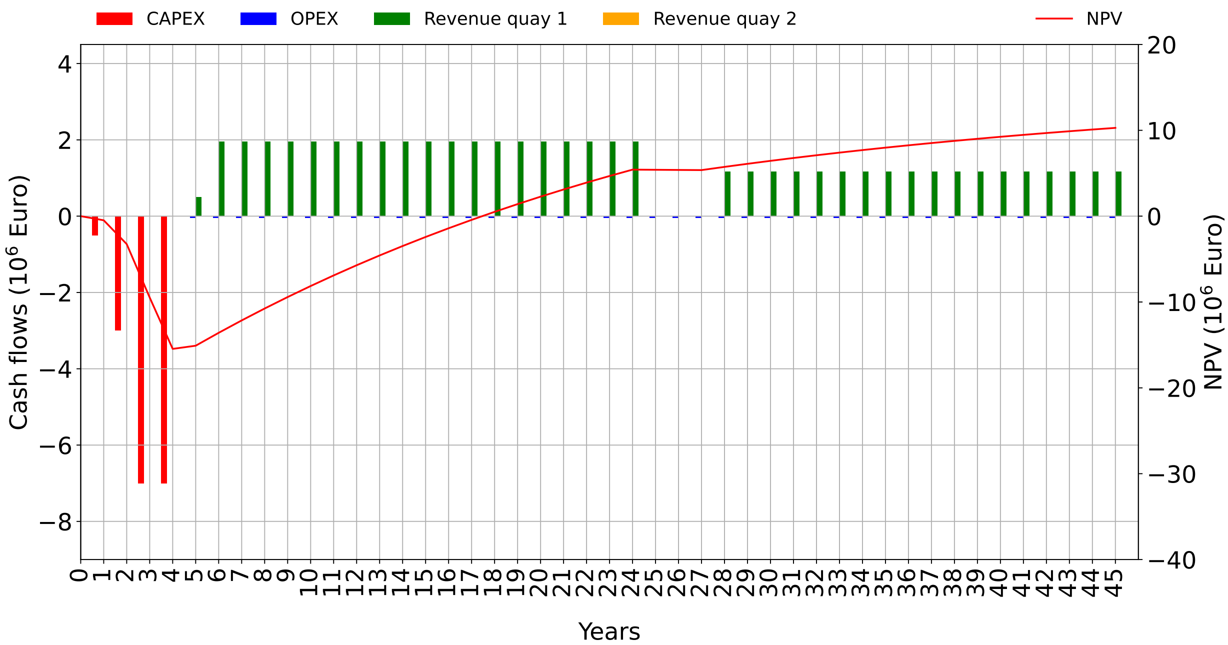


Figure 3.6: NPV calculation Scenario F-1 – 'new quay at a different location', first quay only (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 3.7 presents the cash flows and NPV for the future proof, robust quay wall. It shows that indeed the future proof quay wall requires larger initial investments than the 'fit for purpose' quay wall (as presented in the base case). The future proof quay wall also requires additional investments for the upgrade in year 25, for example for additional capital dredging and/or a new crane rail. However, these investments are much smaller than the investments for the construction of a new quay wall. The NPV becomes positive after 20 years and remains positive. The final NPV after 45 years is 14.6 M€.

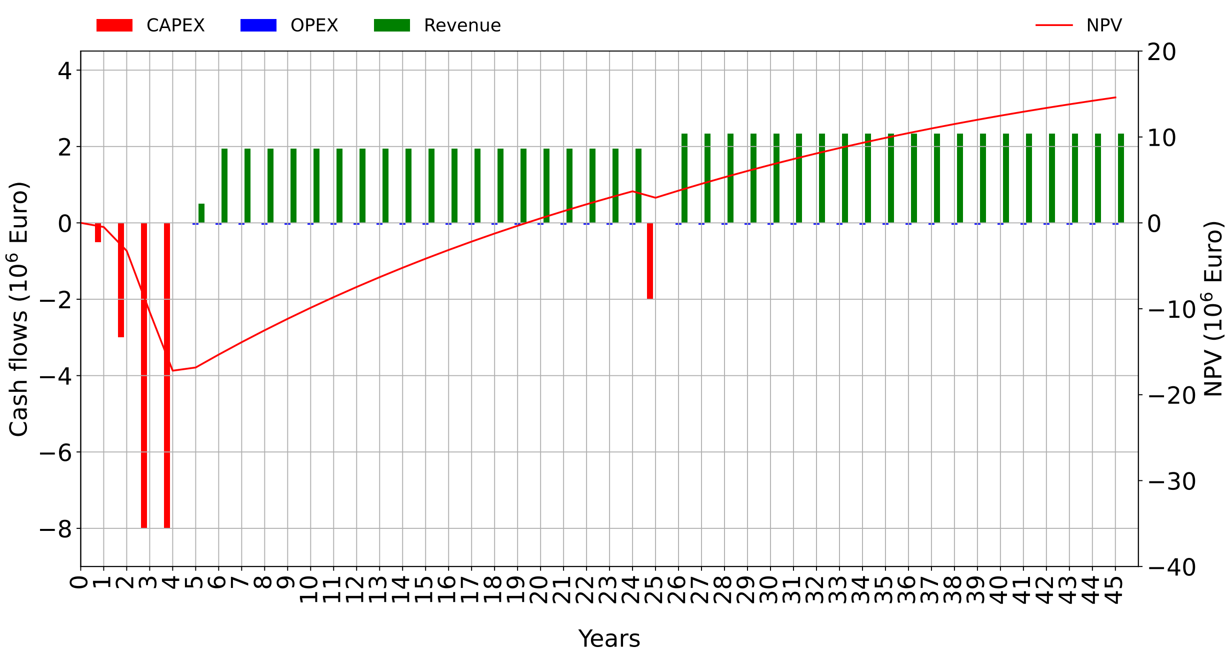


Figure 3.7: NPV calculation Scenario F-2 – 'future proof, robust quay wall' (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

3.2.3 Summary of alternatives

Table 3.5 provides a summary of above alternatives.

Case	Value	Break-even-point (years from start)	NPV (M€)	Internal Rate of Return (IRR)
Base	'fit for purpose' (fulfilling initial requirements)	18	14.7	8.9%
F-1	'new quay at a different location', 'fit for purpose' in Phase 1 but suboptimal in 2	18/ 29	14.0	8.2%
	'new quay at a different location', first quay only	18	10.3	8.2%
F-2	'future proof, robust quay wall'	20	14.6	8.2%

Table 3.5: Summary table (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The port authority can now decide which solution is preferred. The 'fit for purpose' quay wall in the base case requires the smallest investment and returns the largest benefits, assuming nothing changes in the future. The future proof robust quay wall allows the port authority to deal with a certain amount of uncertainty but requires a larger investment upfront. The benefits for the future proof robust quay wall are slightly larger than for the alternative where the port authority has to construct a new quay wall after the first lease period expired.

Whether or not the port authority decides to construct the future proof quay wall depends on:

- the likelihood of finding a new client after the first lease period has ended and the anticipated success at negotiating acceptable lease fees;
- the likelihood of a change in requirements for the quay wall after the first lease period;
- the initial investments for the 'fit for purpose' quay wall;
- the initial investments for the 'future-proof, robust quay wall';
- the applied discount rate.

In this case only three scenarios are considered, viz. 'Base', 'F-1' and 'F-2'. Considering a full range of scenarios would create a solid base for large future investments.

3.3 Adaptive terminal planning

3.3.1 How to transition from one usage to another?

A key challenge faced by port developers is how to handle a transition from one kind of port usage to another. The essence of adaptive planning lies in seeing uncertain developments not as threats, but as opportunities to be seized. For this it is important to obtain insight into the type and order-of-magnitude changes that may expected.

A key example is the change to hydrogen. The energy transition to renewable energy systems views hydrogen as the fuel of the future (see Section 1.1 for a description of hydrogen as a carrier of energy). However, there are still many related uncertainties: In what form will hydrogen be traded in the future (liquefied and gaseous hydrogen, ammonia, liquid organic hydrogen carriers, etc.)? Will it be globally traded or not? Which port in North-Western Europe has the competitive advantage to become a hub? What will be the geopolitical impact once renewable energy flows replace fossil fuel flows? Et cetera.

Nevertheless, ports have to plan now for the future by answering the following questions: Which effective hydrogen supply chains are likely to emerge (connecting supply and demand)? What activities, and corresponding facilities and infrastructure requirements, are associated with these supply chains? Which energy carrier is likely to be the most cost-effective in the given conditions? Can port facilities be established by adapting the existing port infrastructure or should a new terminals and transport infrastructure be built? Ultimately, any investment decision will be based on a viable business-case. For this a thorough supply chain analysis is needed.

Almansoori and Shah (2006) remarked that early Hydrogen Supply Chain (HSC) research focused on individual technologies of the supply chain, such as production, storage, or distribution, rather than dealing with the supply chain as a whole. Li et al. (2019), more recently, provided an extensive literature review of publications on HSC network design. The authors indicate that a "comprehensive study that encompasses all the echelons of an international HSC network" is lacking. Typically vessel transport and the cost of terminals have been out of scope. Lanphen (2019) investigated the influence of shipping distances on price per ton for different hydrogen carriers. Furthermore she developed a method to estimate the required terminal elements and their order-of-magnitude dimensions, for an estimated annual throughput.

The next section discusses a case example of trade-offs in hydrogen import supply chains. Additionally, it describes a method for the functional design of hydrogen import terminals as a function of annual throughput. NB: The case example is fictional and the values in this case illustrate the *principle* of investigating hydrogen supply chains and import terminals only. They should *not* be used as a reference!

3.3.2 Case example: transition to hydrogen

In general, ports foresee four hub functions with the potential for seizing hydrogen opportunities, namely: usage, production, trading, and import. In this example, we focus on the import hub function, where hydrogen is imported and subsequently transported to users in the port and to the hinterland. Two questions are of interest:

1. what hydrogen carrier is most suitable to transport the hydrogen from the export terminal to the import terminal, and
2. given the preferred carrier, what are the key terminal dimensions for a target throughput?

What is the most suitable hydrogen carrier?

Hydrogen is difficult to store because of the low density and low boiling point. Therefore, it is stored under high pressure or at a temperature of -253 °C (Brynolf et al., 2018). Binding hydrogen to another substance could be favourable for transport or storage (Gasunie, 2018). Hydrogen can be attached to a lot of substances, such as Methanol, Ammonia, Formic acid, Ethanol, Dibenzyltoluene, Methylcyclohexane and Sodium borohydride. Lanphen (2019) considered four carriers in her research: Ammonia (NH_3), Methylcyclohexane (MCH), liquefied hydrogen (LH_2) and gaseous hydrogen (H_2). Different hydrogen feedstocks have different characteristics, which determines the way they are transported:

- Ammonia (NH_3) is transported with Liquified Petroleum Gas (LPG) vessels (at a temperature of -33 °C and a capacity of 10,000 to 266,000 m^3);
- Methylcyclohexane (MCH) is a Liquid Organic Hydrogen Carrier (LOHC) that is transported with chemical tankers/oil tankers (with ambient pressure and temperature, and a capacity of 20,000 to 442,000 ton);
- Liquefied Hydrogen (LH_2) is transported with liquefied hydrogen carriers (the first one became operational in 2020) with a temperature of -253 °C.
- Hydrogen in gaseous form is transported through pipelines.

The cost price per carrier type varies with demand volume and per import-export country combination. Lanphen (2019) developed a model that combines the CAPEX and OPEX over a given lifecycle period for an export terminal, transport chain and import terminal. Key elements of the supply chain (such as conversion plants and storage tanks) come with a predefined capacity. As a result, capacity increase occurs in steps. Cost price per ton typically reduces as demand increases; quickly in the beginning, levelling off as demand increases further. So it is important to consider a minimum viable import volume. The carrier type influences the cost price per ton through differences in losses, at the export terminal, during transport and at the import terminal, and differences in costs, associated with transport, storage and conversions steps. Figure 3.8 shows the outcome for a specific export-import terminal combination. In most cases production costs form the largest share of the total cost per ton. Apart from production costs Figure 3.8 illustrates that, for this specific import-export country combination, the highest costs for NH_3 and MCH are associated with the import terminal. For LH_2 the conversion plant costs the most, while for gaseous hydrogen the transport costs are largest. The total costs of NH_3 are lowest.

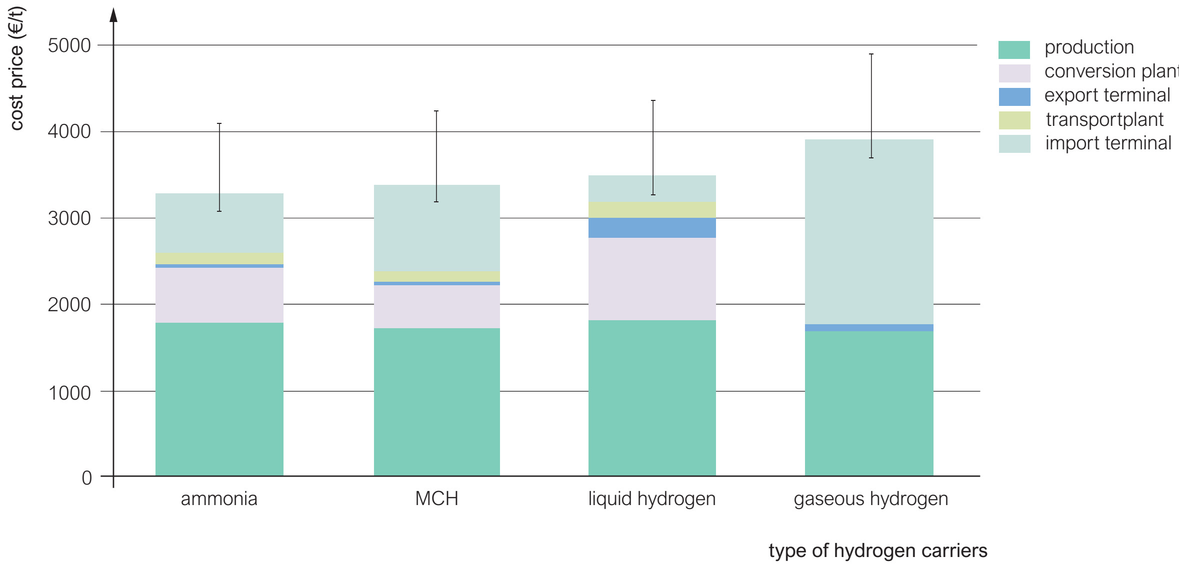


Figure 3.8: Cost price estimate of supplied hydrogen for a demand of 700,000 t/y from Brazil to the Netherlands (reworked from Lanphen, 2019, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Clearly this same analysis can be applied to a range of import-export locations. Figure 3.9 shows the cost totals for import to Rotterdam, but now including a range of export locations. It is interesting to observe that depending on transport distance, carrier preferences can flip. For 'shorter' distances up to about 3000 nm pipeline transport is generally cheaper. Beyond this distance shipping becomes more advantageous. For distances up to 6000 nm NH_3, MCH and LH_2 are more or less equally competitive. For transport distances beyond that MCH and Ammonia become the most cost-effective carrier type.

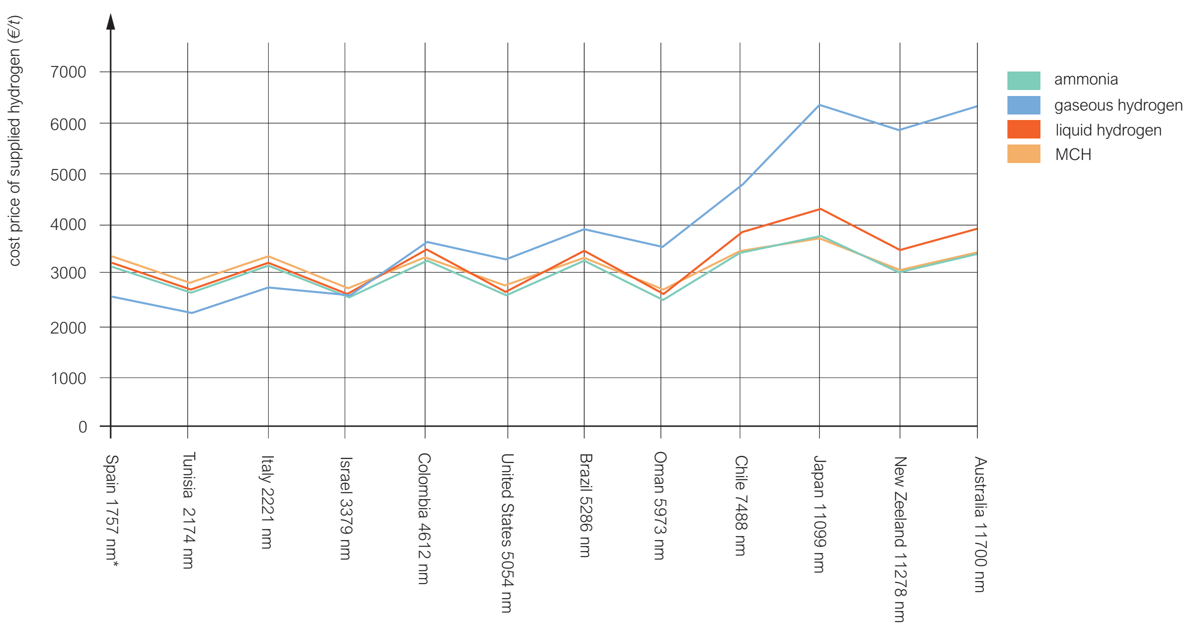


Figure 3.9: Cost price estimate of hydrogen import to Rotterdam from varying with the countries, with a demand of 700,000 t/y (reworked from Lanphen, 2019, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Based on the analysis of potential export locations, one or more preferred carrier types should be identified. The next step is to determine the key terminal dimensions.

What are the key import terminal dimensions?

Unless gaseous H_2 is the preferred carrier type, the import terminal will consist of a liquid bulk terminal layout. Transport will take place with LPG vessels, chemical/oil tanker or LH_2 carriers.

Depending on the anticipated demand, one or more jetties will be required in order to achieve acceptable berth occupancies and associated waiting times. The tanker's pumps will normally be used for unloading, but shore-based pumps may still be required if transshipment with smaller vessels is foreseen.

A next element of the liquid bulk terminal is the area of land that needs to be allocated to storage. The required storage volume is typically governed by the anticipated demand, the maximum size of the calling vessels and foreseen dwell times of the cargo. The total storage volume may be larger when strategic stocks also need to be accommodated. To avoid taking up valuable port space, strategic storage may be done in salt caverns located in the hinterland, or old gasfields more offshore, when possible.

Oil tanks, such as conventional chemical tanks to store MCH, need to conform to safety criteria. Typical safety criteria are that each tank is surrounded by a concrete or earth wall at a specified distance and height, that whenever a full tank collapses, the oil can be contained within the bund (Ligteringen, 2017). Ammonia is stored in a refrigerated tank with a capacity of 15,000 to 60,000 ton and liquefied hydrogen in a cryogenic tank. Liquid hydrogen storage is more dangerous than oil storage, therefore a safety zone and a special safety provision are needed.

Apart from the basic elements of a liguid bulk terminal, viz. jetties, pipeline networks and storage facilities, there are also other carrier-related elements that can have a significant effect on the business-case and space requirement of the alternative solutions (cf. Abrahamse, 2021). The MCH import terminal has the highest costs due to the high energy demand of the H_2 retrieval plant. In the NH_3 terminal the largest costs also originate from the energy demand of the H_2 retrieval as well, while in the liquid hydrogen terminal the largest costs originate from the investment costs for storage.

Systematically estimating the number of terminal elements and their order-of-magnitude dimensions, following the steps described in Part II – Section 3.3.3, is the best way forward to compare alternatives and to gain insight in the numerous complex feedback mechanisms.

How to transition from one kind of land use to another?

As soon as thorough analysis has revealed which hydrogen carrier is preferred for a given import terminal, an estimate of the required terminal facilities and associated land use can be made. Once this functional design is available, including the number of required terminal elements and their order-of-magnitude dimensions, port developers can start to analyse how this new type of port use can best be made a success. In some cases existing port infrastructure may be used, possibly after some modifications. But in other cases completely new infrastructure is needed.

As mentioned at the start of this section, the essence of adaptive planning lies in seeing uncertain developments not as threats but as opportunities. While the energy transition involves a number of large uncertainties, it is clear that significant momentum is developing to move away from a strictly fossil-based economy. Taking a leading role in this transition might attract new business to the port.

4 Waterways and port water areas

This chapter gives some examples of hydrodynamic phenomena and how these may affect water-borne transport systems.

4.1 Hydrodynamic effects on water-borne transport systems

The more supply chains aim at just-in-time delivery, the more they become vulnerable to workability limits and other hydrodynamic phenomena such as droughts. Operability is defined here as the capability to get work done under the conditions present and with the means available. It is the combination of these two attributes that determines operability, so not just the weather conditions, for instance. Even if the weather is fair, operability can be still restricted when water levels are reduced, or when a vessel, (un)loading or construction operation is particularly vulnerable to the ambient conditions.

Figure 4.1: Sea state, a determining factor of workability at sea (photo by RANJITH AR is free to use under www.pexels.com licence).

Various hydrodynamic phenomena can influence the operability of different parts of the supply chain:

- *Open ocean* – the main determining conditions here are wind, waves (Figure 4.1) and currents; vessels sailing at open sea have to exert extra power, hence more fuel and more emission, to maintain the Speed Through Water (STW). Ocean currents may influence their absolute speed (Speed Over Ground (SOG)), which may increase or reduce the time and energy expenditure to a journey. Routing around severe currents may also lead to delays.
- *Offshore mooring and ports* – depending on the location (sheltered or not), offshore port-activities are much more sensitive, for example single buoy mooring, or barge transport in onshore-offshore port systems. Mooring forces must not become too large, vessel motions not too strong and offshore-onshore barge transport not unsafe.
- *Port entrance* – waves and currents (influencing manoeuvrability) and the shape and orientation of the entrance affect the potential for port downtime.

- *In-port manoeuvring* – depending on the amount of tug support available, vessel manoeuvring within a port may be hindered by strong cross-winds. In this case workability is determined by the occurrence of and exposure to high winds, as well as by the availability of tug support.
- *Moored vessels in a port* – have a resonant response to waves of certain frequencies, to the extent that the resulting motions may hamper loading/unloading operations and mooring forces may become unsafely large, forcing the vessel to leave the berth. Thus, operability is determined by the prevailing wave spectrum, the resonance properties of the port basin and the vessel, and the mooring system.
- *Moored vessels along a river* – are sensitive to strong currents, which may lead to overly large mooring forces. Hence operability is determined here by the occurrence of high flows, the degree of sheltering offered by the berth and the mooring system. Another potential cause of operability reduction is extremely low water, due to which the quay can no longer be reached (Figure 4.2), or sailing ships have to pass so close to the moored vessel, that vessel motions and mooring line forces become too large.

Figure 4.2: Tidal harbour of Lillo, province of Antwerp, Belgium, at low tide (image by LimoWreck is licenced under CC BY-SA 3.0).

- IWT – operability for vessels sailing on inland waterways can be influenced by various factors, such as high water (insufficient air draught under bridges), low water (insufficient navigable depth), blockage due to malfunctioning of infrastructure (bridge does not open, lock inaccessible), or blockage due to accidents.

Clearly, operability limits have their effect on the capacity of the supply chain, via delays or throughput reductions. Therefore, it may be worthwhile to invest into measures that increase operability.

Stam (2020) shows, in the case of an offshore-onshore container port system, how operability may influence the feasibility of a design option. The rapid increase in the amount of container transport, combined with the scarcity of available land onshore or the inability to receive still larger vessels, may force port authorities to seek extension offshore. This saves dredging costs, but involves double container handling and offshore-onshore transport, either by a barge shuttle service or via a fixed link (bridge, tunnel). A fixed link is expensive, while barge transport is subject to workability conditions. As a result, the economic feasibility of such a combined port system is not obvious.

Considering only two principal design parameters (design vessel size and distance offshore), Stam (2020) performs an economic feasibility study based on simulation for three different cases (Figure 4.3): (A) an onshore port including capital and maintenance dredging, (B) an onshore-offshore port combination with shuttle barges, subject to workability limits, and (C) an onshore-offshore port combination with a costly fixed link to the shore. The offshore port component includes a buffer stock in order to accommodate temporary mismatches between the throughput over the quay and the offshore-onshore transport system.

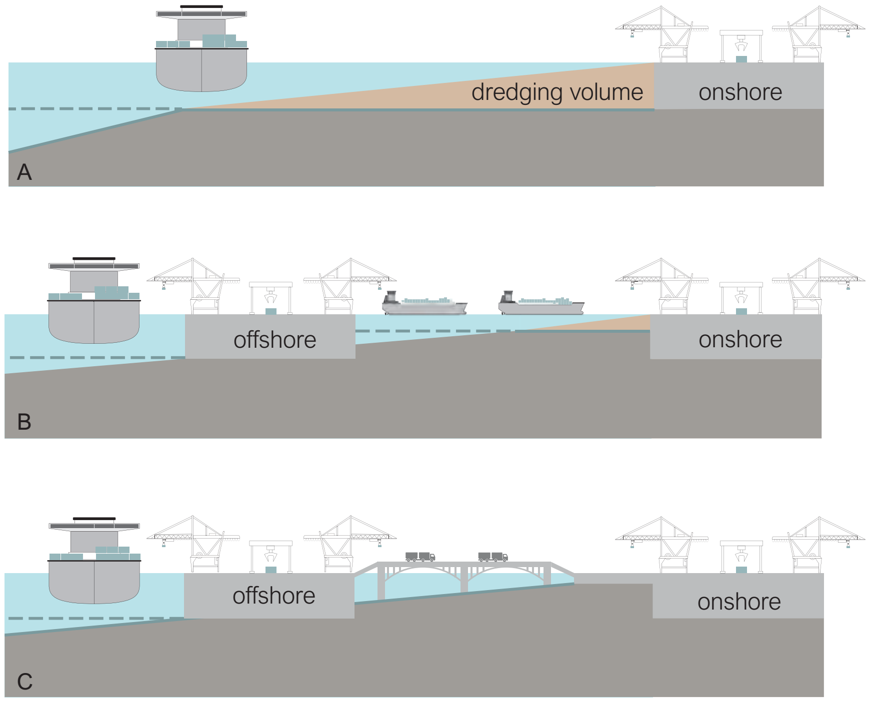


Figure 4.3: Case study of an offshore-onshore port system (reworked from Stam, 2020, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Referring to Stam (2020) for further details of the economic considerations, we focus here on the effect of operability on the costs of the system with a barge shuttle (Case B). Operability limits temporarily affect the capacity of the offshore-onshore system, hence the size of the buffer storage area offshore, which is an important cost item.

Figure 4.4 gives, for the example considered, the relationship between the number of consecutive days of downtime (assumed to occur once per year) and the storage required if waiting times for the sea-going vessels remain within the agreed bounds.

In the example the yearly throughput via the offshore port is 500,000 TEU, which means on average 1370 TEU per day. The increase of the storage requirement per day of consecutive downtime, however, is significantly larger

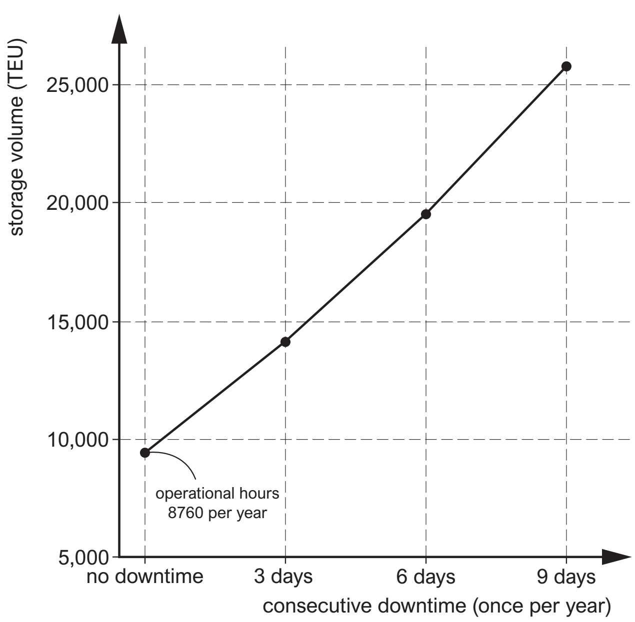


Figure 4.4: Storage volume requirement as a function of downtime (reworked from Stam, 2020, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

(about 2000 TEU/day). This is due to the fact that vessels arrive at random (see Part II – Chapter 4). As the spare capacity of the shuttle barge system will generally not be large, it takes some time for the system to catch up after the downtime.

Apart from the costs of extra storage space, demurrage is another cost item. Demurrage is the charge paid to the shipping line for excess waiting time, above the agreed time. Daily demurrage rates typically range from 75 to 150 US$/TEU. The optimal size of the storage area is largely the result of a trade-off between these cost items.

The left panel of Figure 4.5 shows how in the example considered the downtime influences waiting costs and how this is reduced by increasing the offshore storage capacity. The relationship is nonlinear, because the storage capacity also determines the time needed after the downtime to return to normal. Subsequently, the investment costs involved in creating the storage capacity can be traded off against the capitalised waiting costs (Figure 4.5, right) by seeking for the minimum sum of the two. Note, however, that waiting time is not only an economic issue but overly long waiting times also affect the port's reputation and its competitive edge.

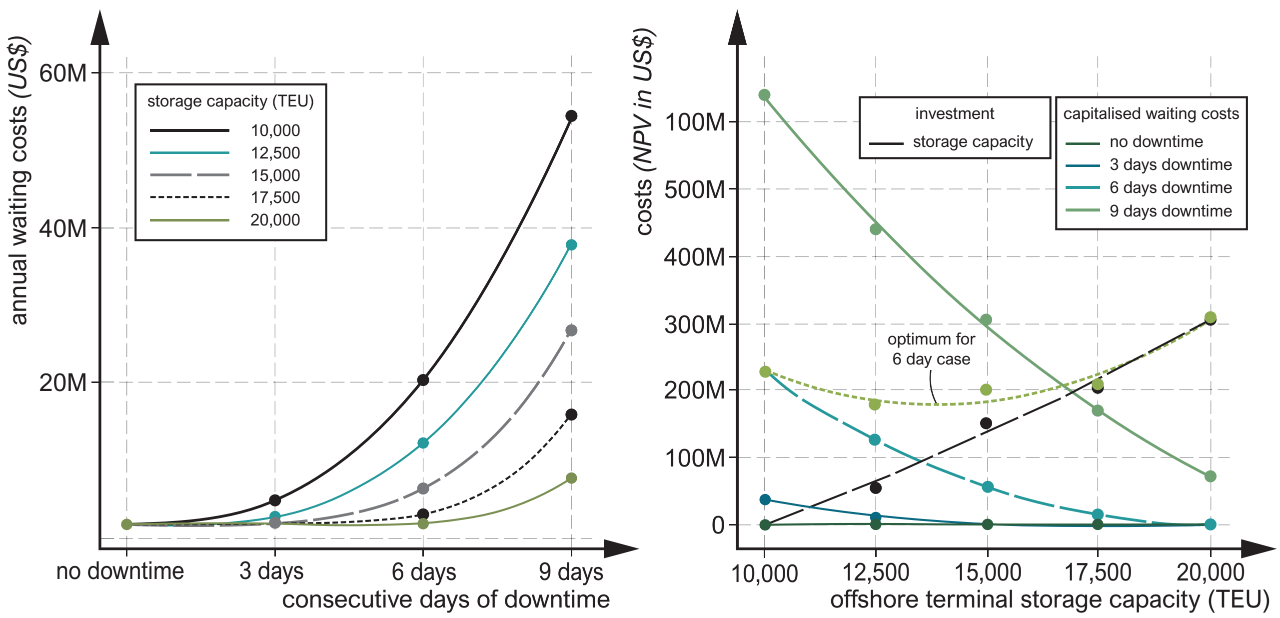


Figure 4.5: Downtime and optimum storage capacity (reworked from Stam, 2020, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The above example concerns a measure (buffer storage capacity) to accommodate downtime by reducing its effects. One may also consider measures to reduce the downtime, itself. Using the same categorisation as above, such measures could be as follows.

Open ocean Vessels sailing at open water are subject to wind, waves and currents. Wind and waves generally tend to reduce the STW, which means more energy expenditure and emissions than in calm water. Routing ships around severe storms usually involves delays, which may mean delayed delivery to the client and the associated costs.

Kim et al. (2017) describe a method to estimate the loss of ship speed due to wind and waves. Figure 4.6 shows some typical results, for an equivalent speed in calm water V_s of 23 knots. The left panel of Figure 4.6 shows that wind and waves can cause significant speed reductions. Compensating this requires a disproportional extra energy consumption, which increases non-linearly as function of the speed (Figure 4.7, left; also see Chapter 5). The right panel of Figure 4.6 shows that even wind and waves astern don't add to the vessel speed.

Ocean currents, such as the Gulf Stream (Figure 4.7, right), influence the SOG rather than the STW. Their effect can be positive or negative, so clever routing can make the difference between costly delays and cost savings (due to slow steaming).

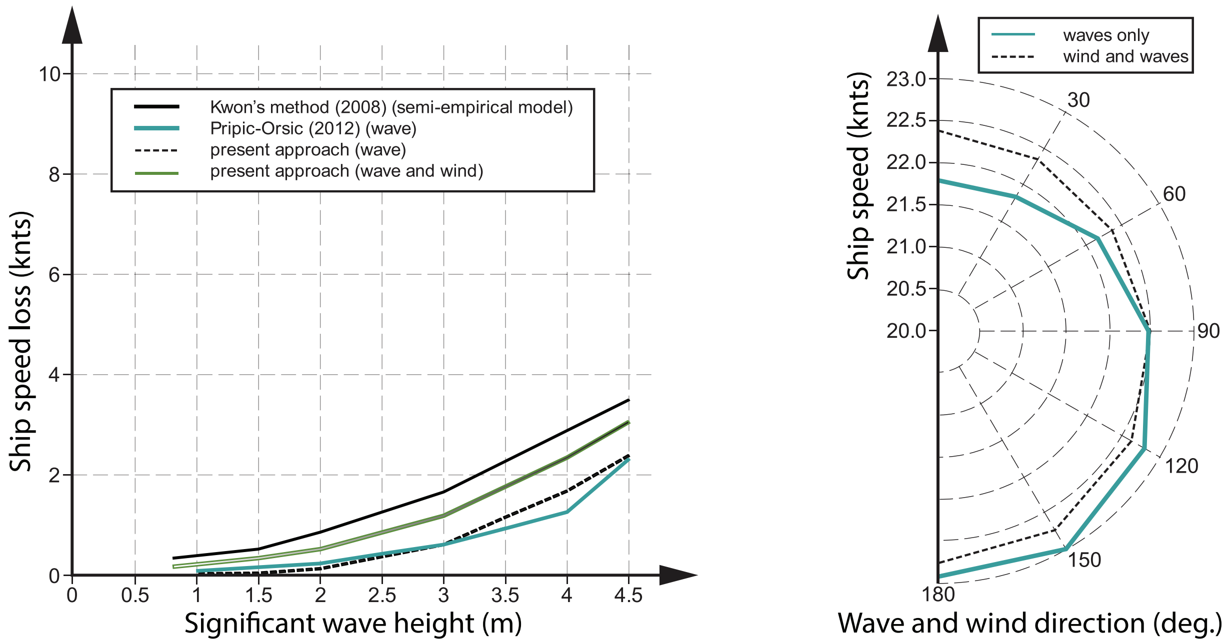


Figure 4.6: Vessel speed loss due to wind and waves at open sea (reworked from Kim et al., 2017, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0). Left: speed loss with wind and waves ahead; right: dependence on wind and wave direction at wind force 6 Beaufort.

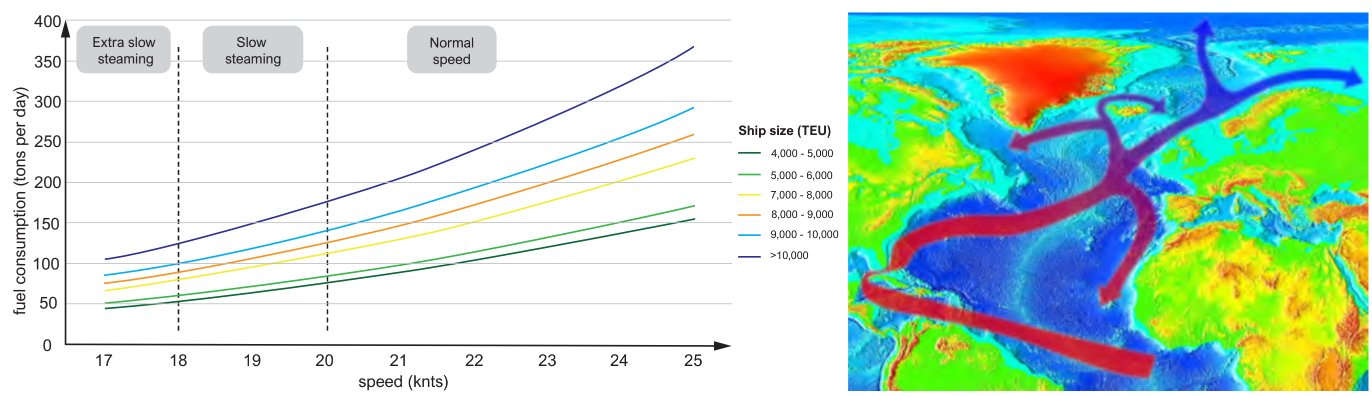


Figure 4.7: Left: Fuel consumption at open water (reworked from Notteboom and Carriou, 2009, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0), right: Mid- and North-Atlantic currents (image by RedAndr is licenced under CC BY-SA 4.0).

Offshore moorings and ports Workability offshore can be enhanced by creating shelter from wind, waves and currents. If the existing topography is suitable (e.g. islands or sheltered bays) this can be achieved by clever location. Otherwise, structural measures are needed, e.g. an artificial port island. In the case of an onshore-offshore port system with shuttle barges, one may also consider alternatives in case of downtime of the barge system, such as a tidal window, or temporarily allowing smaller vessels only, or lightering (if downtimes occur often enough to justify the investment).

Port entrance A different breakwater layout may facilitate entering the port under harsh conditions. The possibility of increased wave penetration, however, is a point of attention. Further see Part II – Section 3.2 and Part III – Section 2.3).

In-port manoeuvring Depending on the frequency of occurrence of troublesome high winds, the availability of extra tug assistance may be an option to increase workability. In the port layout design, the prevailing wind direction can be taken into account when determining the orientation of the quays.

Wind screens (Figure 4.8) are another possible structural measure. Note that the arguments to implement this type of measure are not only the reduction of downtime, but also the risk involved in manoeuvring. In the case of the Caland Canal, for instance, vessels have to take a sharp bend (not shown in Figure 4.8) just before passing the bridge. With unpredictable wind forces, this may involve a risk of material damage and downtime, but also of gas leakage, explosions and life hazard.

Figure 4.8: Wind screens along the Caland Canal, Port of Rotterdam (by Victor Stoeten is licensed under CC BY-NC-SA 4.0).

Moored in port Depending on the wave properties and the port layout, waves penetrating into a port may resonate there and increase in amplitude. A notorious example are seiches, which generally are hardly noticed at sea, but may become significantly larger inside the port and cause unacceptable ship motions there. It is difficult to prevent penetration of such long waves, but one may attempt to change the port's response properties, by a different layout, energy dissipating elements, etc. Dynamic mooring systems can help changing the combined response characteristics of the and its mooring. Further see Section 4.3.

Moored along a river An obvious measure to prevent unwanted current effects on vessels moored along a river is to create shelter from the current. In the design, however, one should keep in mind that shelter also tends to yield sedimentation.

Navigating inland waterways Downtime due to too high water levels on a river is difficult to avoid. This would require costly operations such as raising bridges. Moreover, sailing under these high flow conditions is not free from risk. The impact of blockage due to accidents or malfunctioning of infrastructure can be reduced by designating alternative routes beforehand (see Part I – Chapter 2 for the example of the accident at the Grave weir). The effects of low water on water-borne supply chains are discussed in more detail in the next subsection.

4.1.1 Droughts and IWT supply chains

Especially in rain-fed rivers, droughts come with low river discharges. But also mixed-source rivers may exhibit times of low discharge. If the river is canalised, like the Maas, the water is retained behind weirs and navigability is guaranteed, although the loss of water via the locks is a point of attention. In open rivers, like the Rhine downstream of Iffezheim in Germany, navigability is often guaranteed during a minimum number of days per year in an average year. In the case of the Rhine, this is defined by the discharge that is exceeded 95% of the time, the Agreed Low Discharge (ALD), at present 1020 m^3/s at Lobith, near the Dutch-German border. Via model computations this is translated to an Agreed Low Waterlevel (ALW) at every point along the river. The bed of the navigation channel in the Waal and Lower Rhine, the main IWT fairway, is kept at 2.8 m below this level. The IWT system is tuned to this guaranteed navigable depth.

In times of drought, effects of low river discharges can to some extent be compensated by measures such as (also see Ecorys, 2011):

- reducing the load factor of the vessels,
- taking an alternative route with more navigable depth,
- using vessels with a smaller draught,
- a different operational concept, e.g. 24/7,
- shifting cargo to a different transport mode,
- temporary storage of cargo and stock depletion by the client,
- adaptation of production processes to defer the transport of raw materials,
- pro-active stockage.

In very dry years, the discharge falls below ALD for much longer than the agreed 5% of the time (Kramer et al., 2019). In 2018, for instance, this was almost four months in a row (Figure 4.9).

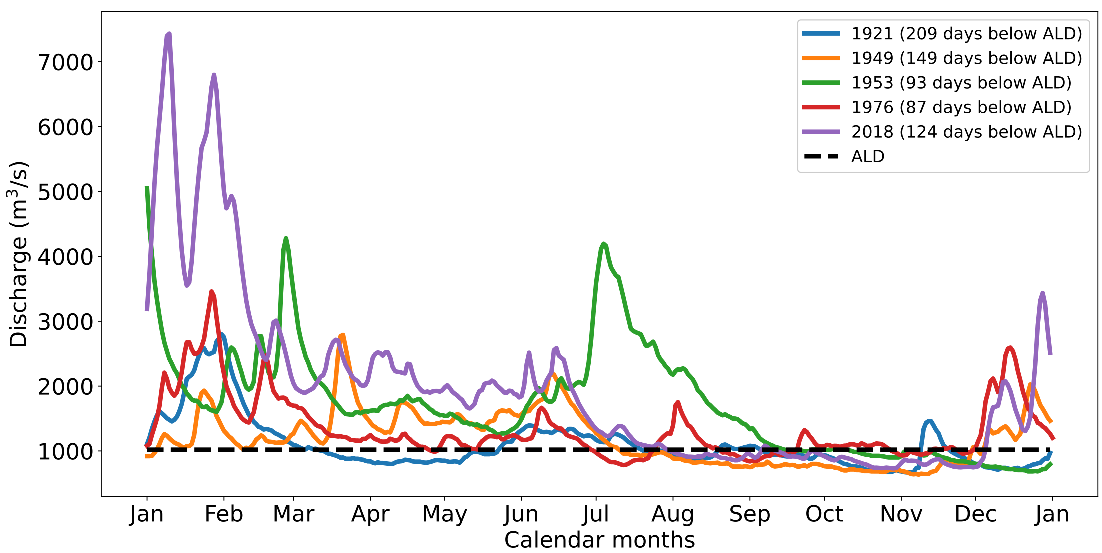


Figure 4.9: Rhine discharge at Lobith during a number of dry years (data provided by Rijkswaterstaat, image by TU Delft - Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Clearly, this has its effects on IWT, as Figure 4.10 shows for dry bulk transport. Apart from the intuitive consequences of low water, viz. vessels adapting their cargo loads to reduce draught, which leads to an increased number of trips to transport the same amount of cargo, Figure 4.10 clearly shows that as the river discharge changes, so does the fleet composition. Vinke et al. (2022) show that as soon as the discharge fell below ALD, the larger push-barge convoys dropped out. The smaller ones could carry on somewhat longer, but ultimately had to give up, as well. The relatively small Rhine vessels remained unaffected and profited from the increased demand. The same applied, even more so, to the coupled barges. Yet, this increased activity of smaller vessels could not compensate entirely for the capacity loss, as the cumulative curve shows. This general picture of reduced transport performance, viz. more trips with less cargo per trip and less total capacity, is confirmed by data from Statistics Netherlands (CBS) from that same period, as shown in Figure 4.11.

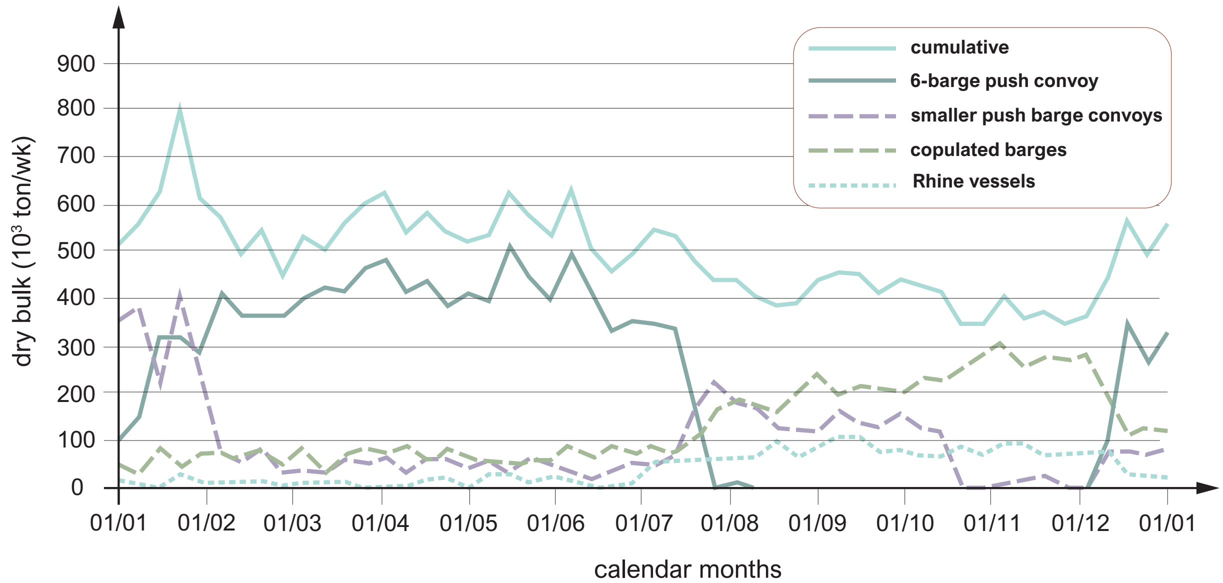


Figure 4.10: Response of dry bulk transport on the Rhine corridor to the 2018 drought (data provided by Rijkswaterstaat, image by TU Delft - Ports and Waterways is licenced under CC BY-NC-SA 4.0).

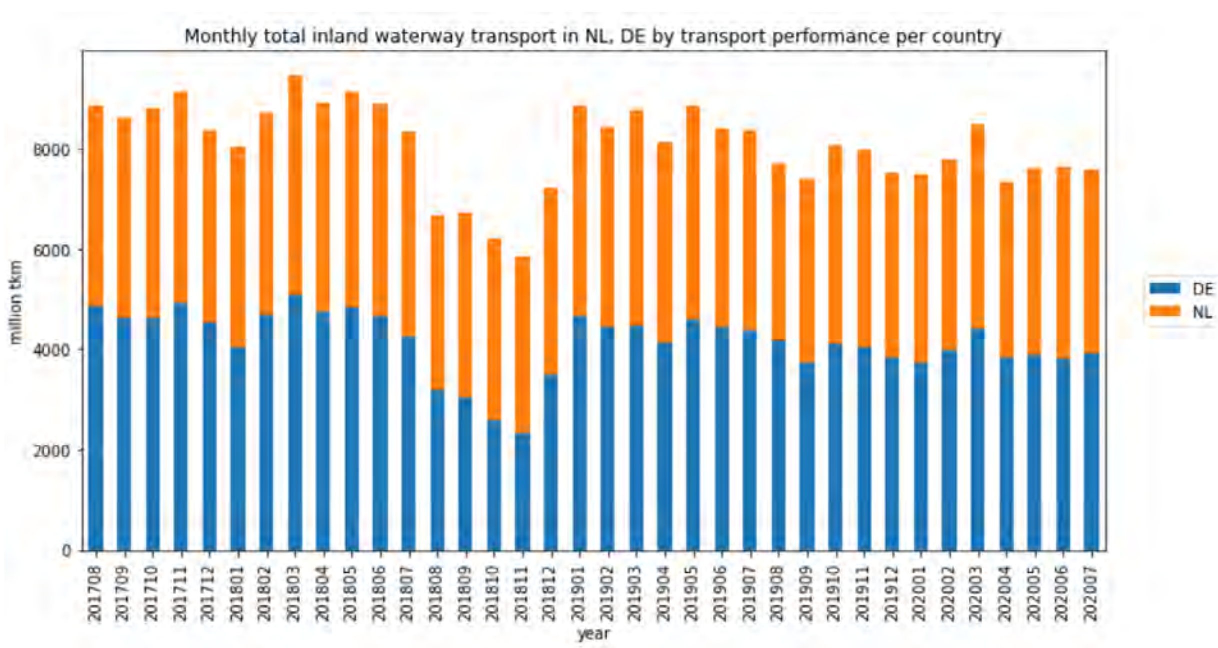


Figure 4.11: Influence of the 2018 drought on the total IWT transport performance in the Netherlands and Germany (data provided by CBS, image by TU Delft - Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Apart from carrying less cargo, the vessels also sail slower, because they are loaded up to the maximum allowable draught. As a consequence, they experience on average more resistance while sailing. So, it takes not only more trips to transport the same amount of cargo, but it also takes longer per trip, even if there is no hindrance from other vessels. Moreover, the larger number of vessels leads to a higher traffic intensity, hence a reduced capacity of the waterway (see Section 2.2.2). Vinke et al. (2022) showed with an agent-based simulation model (OpenCLSim) that depth bottlenecks way up in the hinterland, triggered an increase in IWT port calls in the Port of Rotterdam, a phenomenon that can also be observed in Automatic Identification System (AIS) data of that period. This increased traffic intensity in turn contributed to port congestion and delays.

Yet, changes in fleet composition, an increased numbers of trips and extra resistance are not the only cause of delays during droughts. Especially in rivers, the navigable width also decreases (Figure 4.12). This means that vessels have less space for manoeuvres such as overtaking. Hence the risk of accidents or grounding incidents increases, the more so because the traffic intensity increases. This explains why during the 2018 drought Rijkswaterstaat issued a ban on overtaking for various parts of the Dutch waterway network. As a consequence, traffic congestion occurred at various bottlenecks in the system. The right panel of Figure 4.12 shows that the mean navigable width is equal to the guaranteed 200 m at ALD (1020 m^3/s at Lobith), but decreases significantly at lower discharges, down to 123 m at 600 m^3/s. At bottlenecks, the decrease is even stronger, to less than a third of the width at ALD. Based on traffic simulations with SIMDAS, Verschuren (2020) shows that in this part of the river the width reduction had a stronger effect on the delays than the depth reduction or the increased traffic intensity.

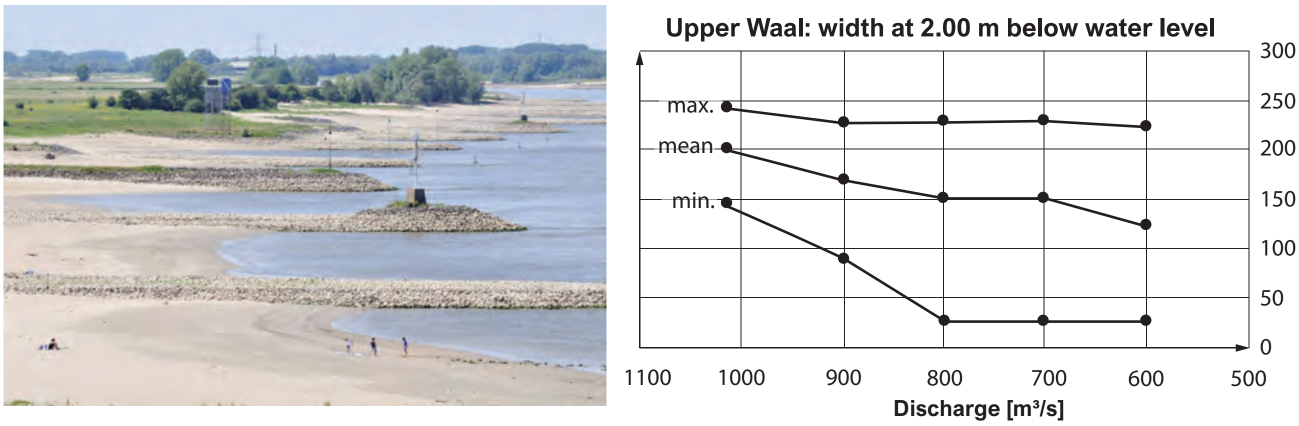


Figure 4.12: Reduced navigable width at low water (left: beeldbank.rws.nl, Rijkswaterstaat, by Martin van Lokven; right: reworked from Verschuren (2020) by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

These consequences of low discharge extremes on the IWT transport mode, clearly underline that ports and waterways should be viewed as integral parts of a coherent system. The complex interplay between water motion, state of the infrastructure, vessel behaviour and logistics needs to be understood fully in order to understand what is happening and to enable the rational design of mitigating measures. The next sections discuss some other examples of hydrodynamic effects on supply chains.

4.2 Hydrodynamic effects during locking

In Part III we have discussed the hydrodynamic phenomena during locking, but did not focus on the forces exerted on the vessels during the locking process and the consequences for locking times and mooring forces.

4.2.1 Entering the lock

When a vessel enters a lock, it experiences a more or less sudden reduction of the cross-sectional area. As a consequence, the return flow and the water level draw-down suddenly increase. On the one hand, this enhances the resistance the vessel encounters; on the other hand it sends a translatory wave into the lock chamber, and a smaller one into the approach channel.

The wave in the lock chamber bounces against the closed gate, comes back and hits the vessel, thus causing even more resistance (Figure 4.13). These effects will obviously be stronger as the blockage factor increases. The right panel of Figure 4.13 clearly illustrates this: the velocity reduction of a small motor ship (dash-dotted line) is much less than that of the pushed convoys.

Measurements in a physical scale model of the new sea lock at IJmuiden give more quantitative information. Figure 4.14 shows the experimental set-up, Figure 4.15 the principal results.

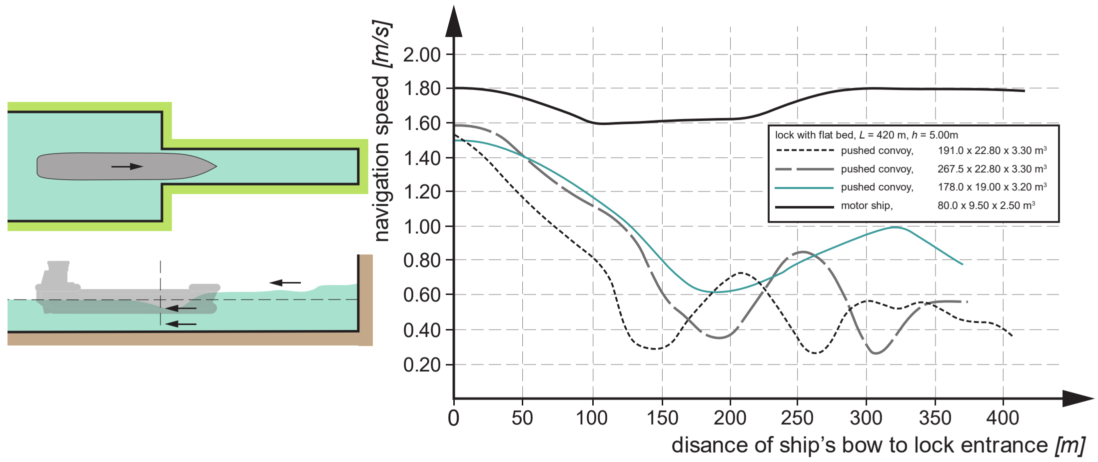


Figure 4.13: Hydrodynamic phenomena during lock entrance (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 4.14: Overview of the physical scale model of the new IJmuiden sea lock (source: Deltares).

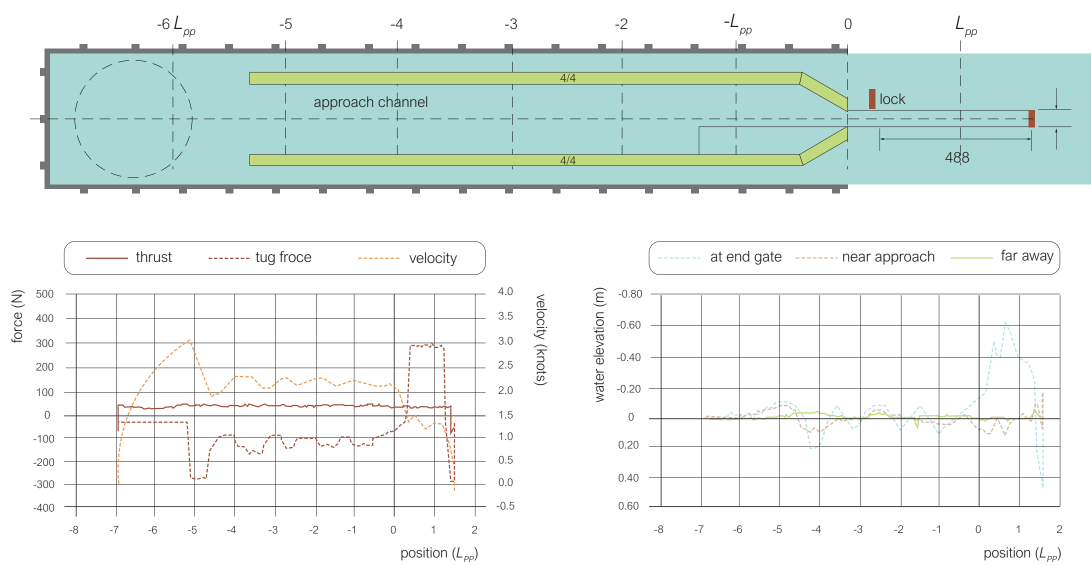


Figure 4.15: Example of experimental results from the IJmuiden scale model (source: Deltares). Image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0.

When the translatory wave bounces against the closed gate (Figure 4.16), it exerts a pressure force that may damage the gate. This force is a function of the maximum wave height z_{max} at the gate, hence of the vessel speed and the blockage factor:

$$\frac{z_{max}}{h_0} = 1.44\frac{V_s^2}{gh_0}\frac{A_s/A_{lock}}{1 - A_s/A_{lock}} \tag{4.1}$$

in which the coefficient has been determined empirically. The length of the vessel turns out to be less important.

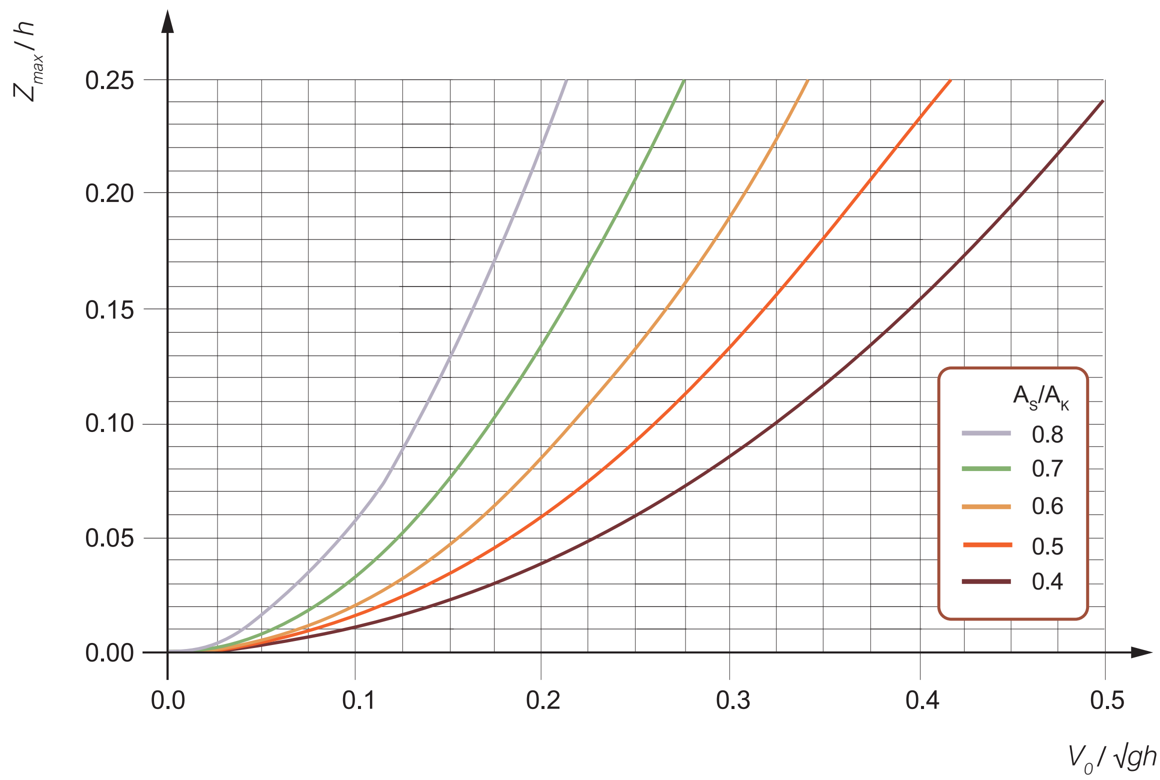


Figure 4.16: Maximum height of the translatory wave at the closed gate (image by TU Delft - Ports and Waterways is licenced under CC BY-NC-SA 4.0).

In order to prevent damage to the gate, the vessel entrance speed is restricted. Another reason to do so is that other vessels that are already in the lock chamber will experience the effect of the translatory wave, in the form of ship motions and/or mooring line forces. As the allowable forces on a vessel or its mooring lines are expressed as a percentage of the vessel's water displacement, the speed restriction will be more severe if there are small vessels in the lock chamber. This may even influence the lock capacity.

Lock entrance can also be simulated with a Computational Fluid Dynamics (CFD) model. Though quite computationally demanding, such a model is able to capture the physics of hydrodynamic phenomena during locking operations. This includes viscous effects, which become important in very confined areas, e.g. at large values of the blockage factor. Figure 4.17 gives a typical result of such a model.

4.2.2 Forces when filling the lock chamber

There are various options to fill a lock chamber, e.g.

- by opening valves in the lock gates,
- by opening culverts in the chamber walls,
- by lifting or tilting the end gate.

In Part III - Chapter 4 we have described how the water level in the chamber responds to the opening procedure. Here we will consider the forces exerted on a vessel in the chamber. In order to prevent overloading or even

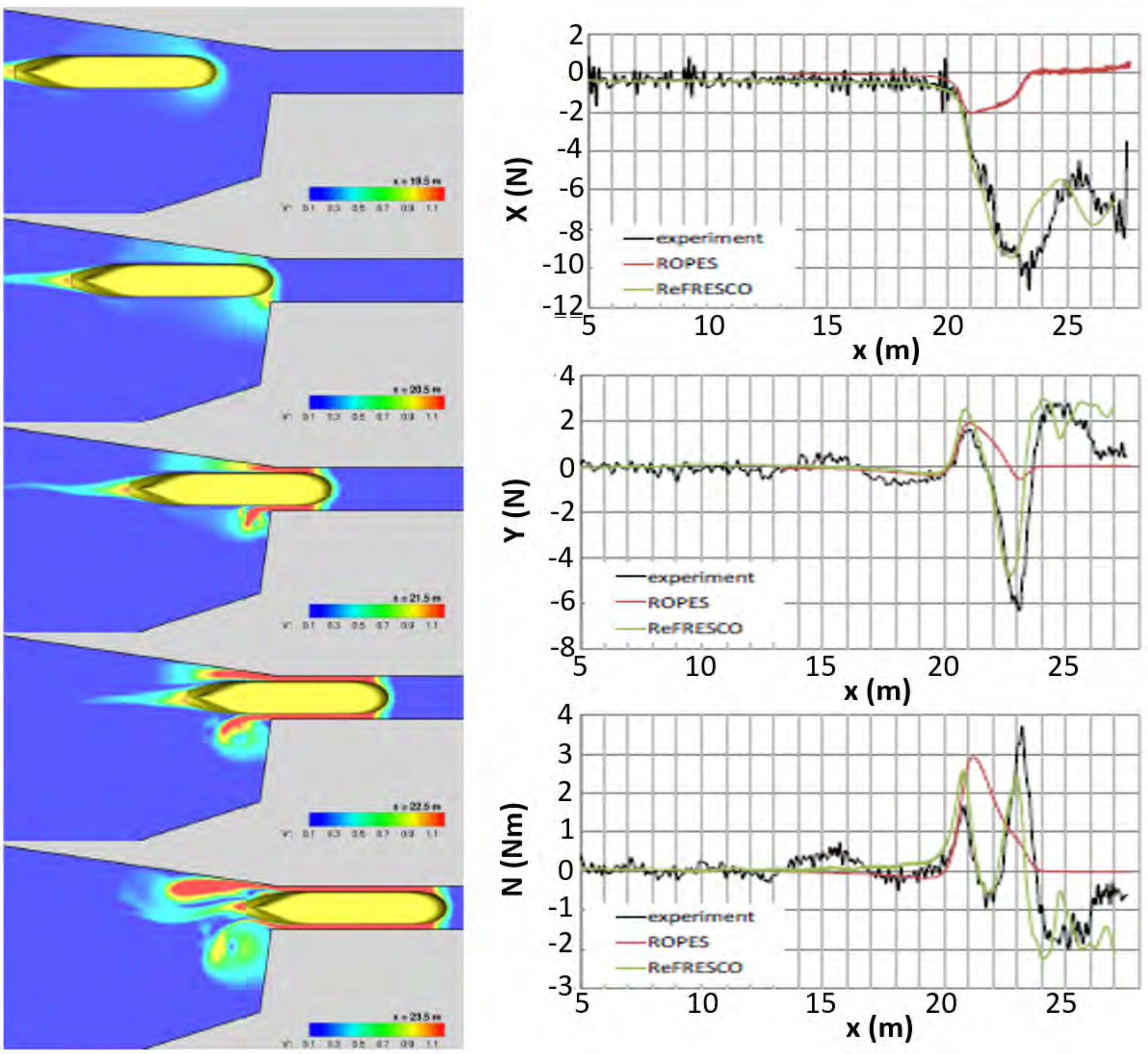


Figure 4.17: Numerical model results for a ship entering a lock (Toxopeus and Bhawsinka, 2016); left: velocity fields; right: longitudinal and transverse forces and moment exerted on the vessel. Images are licensed under CC BY 4.0.

snapping of mooring lines (a dangerous event especially for people on the lock platform), these forces are limited. Such limitations are expressed as a permillage of the vessel's weight (water displacement). Table 4.1 gives the numbers for some IWT vessel classes.

Vessel class	**Maximum mooring line forces (‰ of water displacement)**	
	during filling	**during emptying**
CEMT Class III	1.50	2.00
CEMT Class IV	1.10	1.50
CEMT Class Va	0.85	1.15

Table 4.1: Maximum mooring line forces during lock chamber filling or emptying (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The forces exerted on a vessel during filling consist of various components. Figure 4.18 summarises them for the case of filling through the end gate. Note the importance of water level gradients inside the chamber.

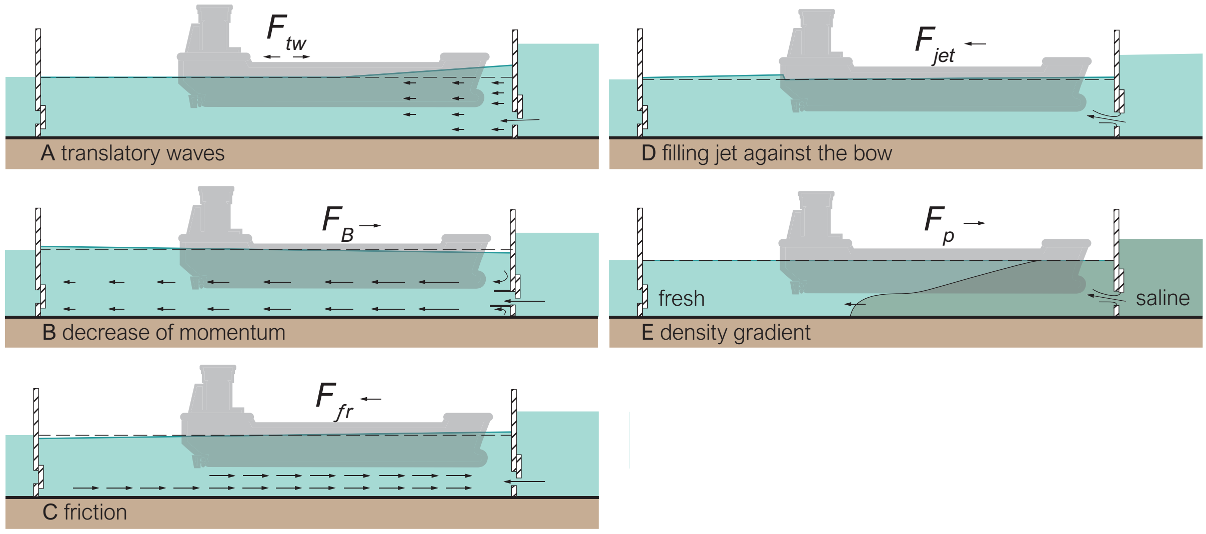


Figure 4.18: Forces exerted on a ship during lock filling (reworked from Glerum and Vrijburcht, 2000, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The force due to a translatory wave, for instance, can be evaluated as follows (also see Figure 4.19):

$$F_{tw} = B_s \left[\frac{1}{2}\rho_w g \left(z + D_s\right)^2 - \frac{1}{2}\rho_w g D_s^2 \right] = \rho_w g B_s \left(z D_s + \frac{1}{2} z^2 \right) \tag{4.2}$$

When ignoring the (small) quadratic term, this becomes:

$$F_{tw} = \rho_w g B_s L_s D_s \frac{z}{L_s} = \text{water displacement} \times \text{water level slope over the ship} \tag{4.3}$$

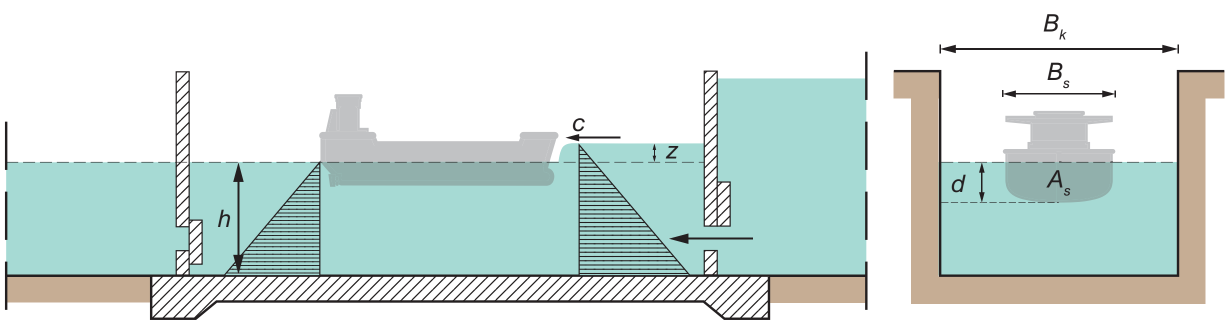


Figure 4.19: Force exerted on a ship by a translatory wave (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The contribution of the jet force can be taken into account by adding the difference in momentum flux at the bow and the stern, respectively (Van Loon, 2017):

$$F_{ship} = S_b + \frac{1}{2}\rho_w g h_b^2 - \rho_w \frac{Q^2}{A_{lock,s}} - \frac{1}{2}\rho_w g h_s^2 \tag{4.4}$$

in which the suffix b refers to the bow and the suffix s to the stern of the ship. Furthermore, S_b is the momentum flux of the jet hitting the bow of the ship, Q the jet discharge and $A_{lock,s}$ the cross-sectional area of the lock chamber just behind the stern. Figure 4.20 presents results from laboratory measurements, showing how the jet force depends on the under keel clearance and the distance of the ship from the gate ($x_{b,min}$ is the minimum allowable distance of the bow from the gate). Note that for large Under Keel Clearance (UKC) values the force can become negative, due to the head difference between bow and stern. Also note that the dependence on the distance to the gate is non-trivial.

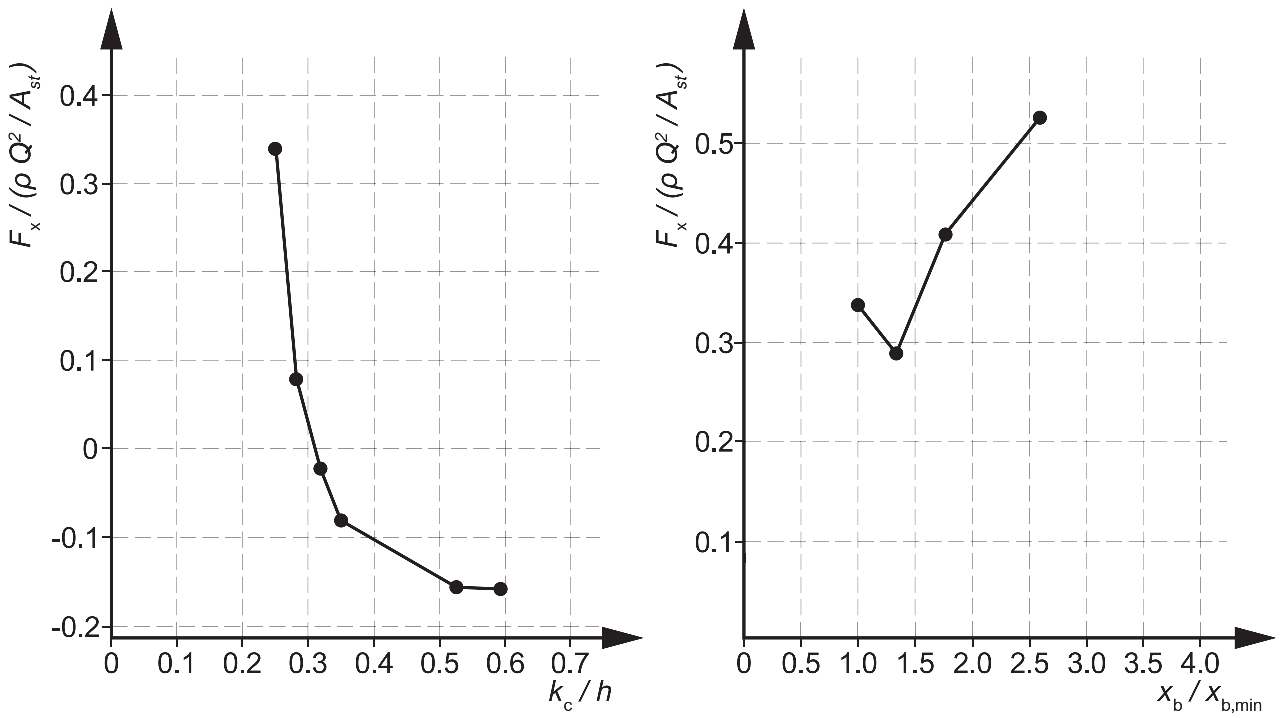


Figure 4.20: Jet force dependence on under keel clearance and distance from the gate (reworked from Van Loon, 2017, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

The forces exerted on a ship during locking can also be determined with a physical scale model, or with a numerical model. Figure 4.21 shows an example from a scale model of a lock with a large bulk container. The results clearly show the effect of the translatory waves during filling, as well as the disturbance that remains after the chamber has been filled.

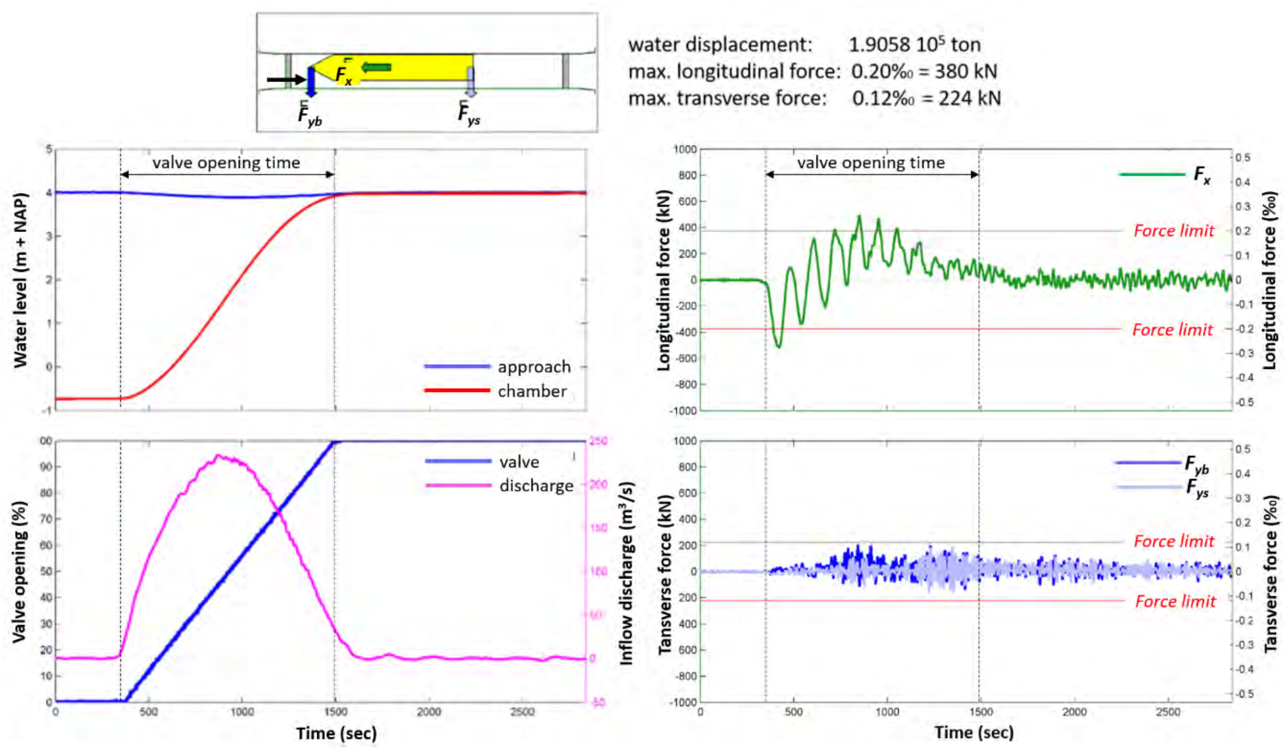


Figure 4.21: Forces exerted on a ship during lock filling (scale model experiment) (source: Deltares).

4.2.3 Forces when emptying the lock chamber

When the lock chamber is emptied, the ship is exposed to forces, again, though with less constituents (Figure 4.22). The effects of the filling jet and the density gradient are missing now, the former because the jet is directed out of the chamber now, the latter because there is no water with a different density entering the lock.

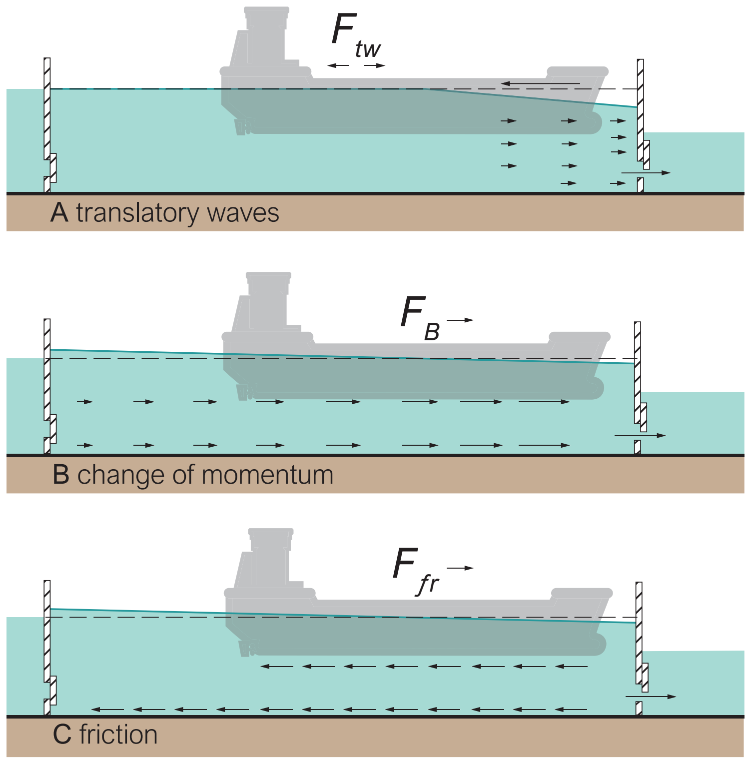


Figure 4.22: Forces on a ship during lock emptying (reworked from Glerum and Vrijburcht, 2000, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

4.2.4 Exiting the lock

During lock exit, the vessel first passes the narrow lock section, where it creates a water level set-down and a return current. Depending on the blockage ratio, it also pushes water out of the lock, thus sending a negative translation wave into the lock and a lower positive one into the downstream channel (Figure 4.23).

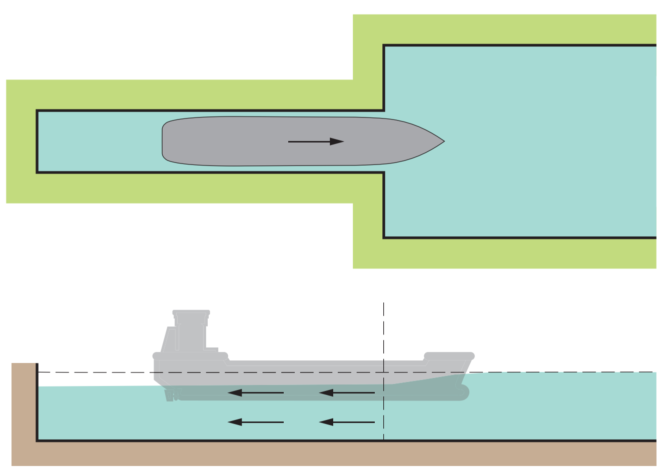


Figure 4.23: Hydrodynamic phenomena during lock exit (reworked from Glerum and Vrijburcht, 2000, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Experiments in a scale model of the new locks of the Panama Canal (Vantorre et al., 2012) give an impression of the forces exerted on a ship, in this case a large container carrier (12,000 TEU, 265 x 46 x 15.2 m), when it leaves the lock (Figure 4.24). Note that when the stern leaves the lock (bow position at L_{pp}) the vessel undergoes a strong positive force and the tugs have to exert an opposite force in order to keep it at the desired speed.

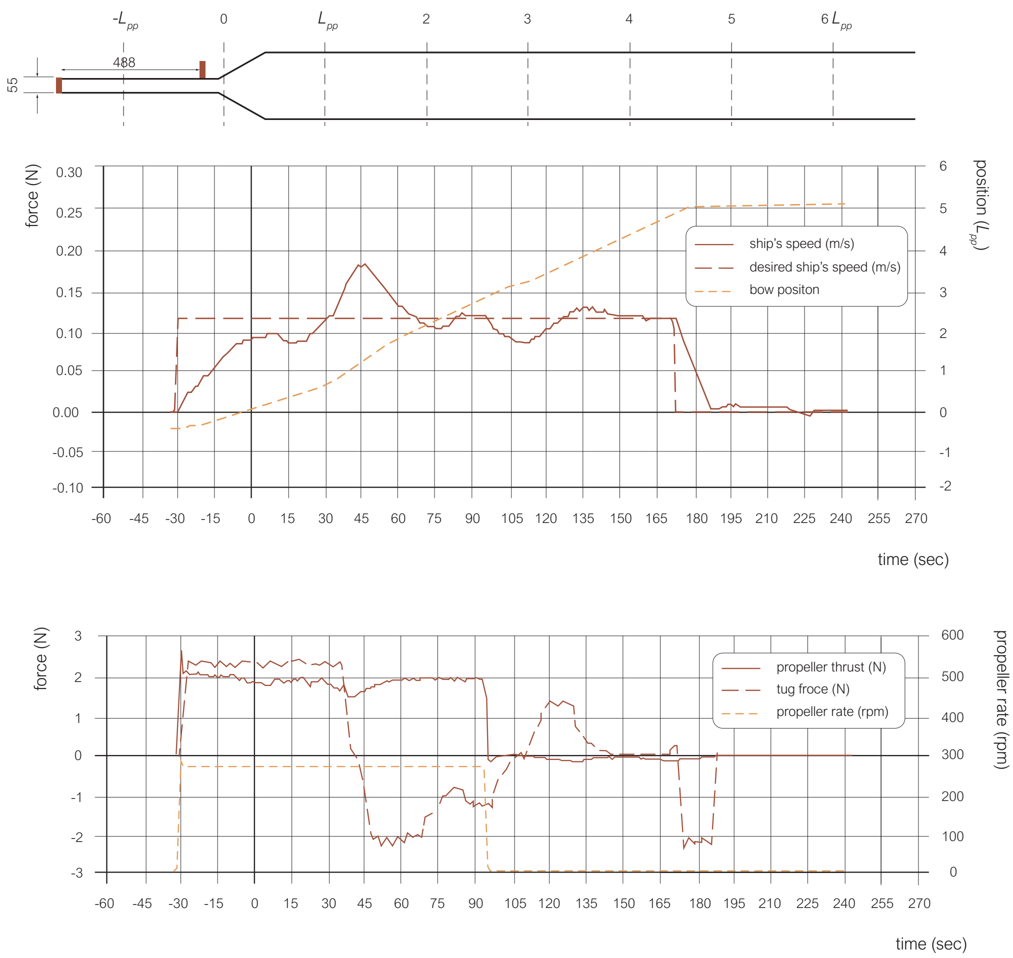


Figure 4.24: Forces exerted on a ship that leaves a lock (reworked from Vantorre et al., 2012, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

4.3 Hydrodynamic effects on moored vessels

Loading and offloading operations may require an evaluation of the hydrodynamic loads if there are safety risks (of snapping lines or even vessels breaking free) or the risk of downtime (reduced cargo handling capacity). In general, moored vessels move due to wind and long (infra-gravity) waves. Additionally, vessels moored in harbours may experience effects of passing vessels, and vessels moored at exposed terminals also encounter sea and swell waves, and possibly currents.

A Dynamic Mooring Analysis (DMA) is executed to evaluate the motions of moored vessels and the loads in the mooring lines. This is done based on information about the environmental conditions, vessel characteristics and mooring configuration.

4.3.1 Analysis input

Environmental conditions that are considered in the analysis are combinations of wind, current, and sea/swell waves or waves due to passing ships. A wave spectrum represents a particular wave condition at a certain location by a superposition of regular wave components. The frequencies of these wave components are given on the horizontal axis and their energy density is given on the vertical axis. Part II – Figure 2.24 shows all relevant wave types and their frequency ranges.

The vessel characteristics required for the mooring analysis are related to calculating the forces and moments on the vessel due to wind, current and waves. For wind and current, coefficients and areas are used to determine the forces and moments on the vessel due to a wind/current of a certain speed and certain direction with respect to the vessel. For waves, a database of Response Amplitude Operators (RAOs) is required. This indicates the response amplitude of the vessel to a wave component with an amplitude of 1 m, for the entire range of wave frequencies, for the entire range of relative wave directions, and for all six degrees of freedom.

Figure 4.25 (left) shows the response spectrum of a tanker in beam seas for the heave motion. It can be seen that for long waves (small frequencies) the RAO is about 1, indicating that the response amplitude is equal to the wave amplitude. The vessel simply slowly moves up and down along with the incoming wave. Towards a frequency of 0.5 rad/s (12.5 s), the RAO increases to 1.6, indicating the natural frequency for heave. For very short waves, the vessel does not move at all. Figure 4.25 (middle) shows the response spectrum of the tanker for pitch in head waves. The natural frequency is at about 0.6 rad/s. The large peak at 0.4 rad/s indicates the wave length, that is approximately equal to the vessel length. Thus, by looking at the response spectra of the vessel and comparing these to the wave spectrum, an estimate can be made of which wave frequencies might cause (extreme) motions of the vessel.

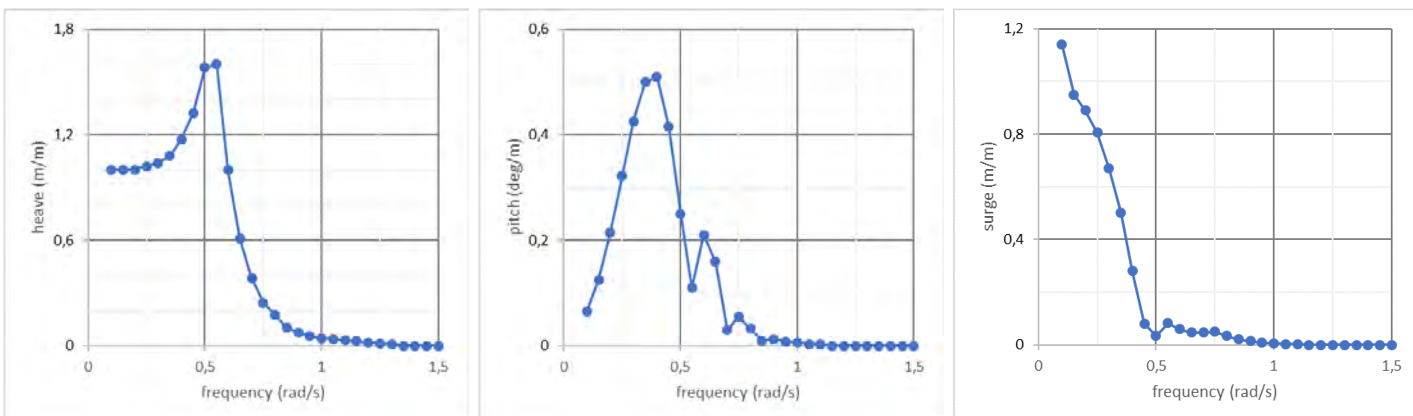


Figure 4.25: Typical RAOs for a tanker shaped vessel (left: heave motion in beam seas; middle: pitch motion in head seas; left: surge motion in head waves). Images by TU Delft – Ports and Waterways are licenced under CC BY-NC-SA 4.0.

As a final input, the mooring configuration is required. This includes the mooring line properties (length, elasticity), fenders and possibly tools for dampening the vessel motions (see Figure 4.26).

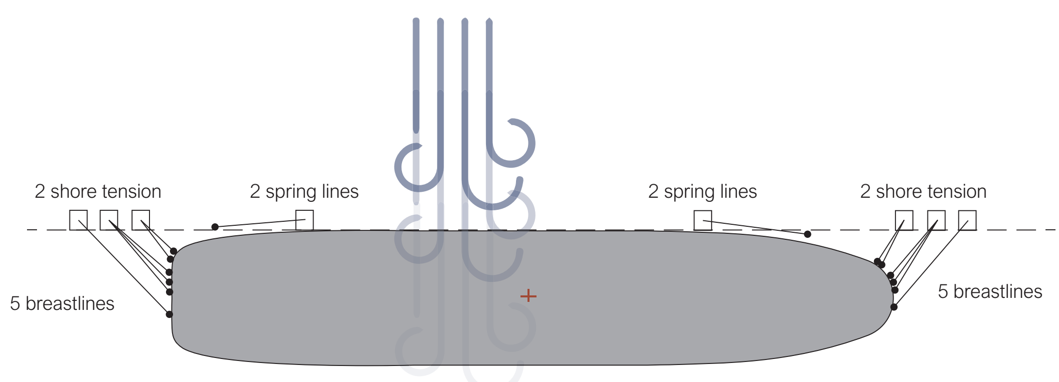


Figure 4.26: An example of a mooring layout (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

4.3.2 Time domain simulation

Based on the input, a simulation is conducted to obtain the vessel motions and forces in the mooring lines. This simulation is done in time domain, so all information captured in the frequency domain is translated to the time domain. One simulation is executed for each combination of input parameters.

Often, a large number of environmental conditions is evaluated, ranging from day-to-day conditions to extreme conditions. To assess which layout of mooring lines, fenders and damping tools allows for the highest uptime and smallest safety risk, multiple mooring configurations are evaluated. On top of that, multiple vessel draughts may need to be evaluated, resulting in the assessment of several vessel databases and coefficients. As a result, the number of simulations to be executed increases rapidly.

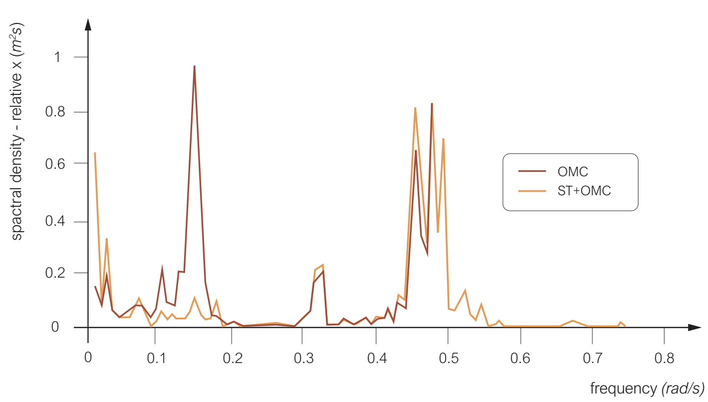
After post-processing and analysing all simulation results, the (extreme) vessel motions and (extreme) mooring forces are reported. A comparison of the performance of the various mooring configurations is then made. Based on this, recommendations can be made for the best mooring configuration to use, and the effectiveness of additional damping tools.

4.3.3 Dampening measures

In case it is found in the DMA that a conventional mooring configuration has a high risk of downtime or even safety issues, additional measures are considered. As can be seen in Figure 4.25 (right), the surge motion of a vessel is sensitive to low frequent excitations. Examples of low frequent excitations are wind, long period waves and passing vessels; all typical effects that are encountered by a moored vessel. As a result, the moored vessel may start to move excessively in surge direction.

ShoreTension is a system designed by the Royal Boatmen Association Eendracht (KRVE) to dampen the horizontal vessel motions in the frequency range around the natural frequency of the system. The system absorbs vessel motion energy by adding a cylinder to the mooring lines that pays out and heaves in line length, ensuring a constant line tension.

Figure 4.27 indicates the effect of the ShoreTension system on a moored heavy transport vessel. The blue graph indicates the spectral density for the vessel with original mooring configuration, and the purple graph indicates that of the same vessel with the ShoreTension system as part of the mooring configuration. For the surge motion (Figure 4.27, top), the ShoreTension system is capable of significantly reducing the slowly varying horizontal motions (around the natural frequency of the system of 0.15 rad/s). There is however another peak present for this moored vessel configuration, between 0.4 and 0.5 rad/s. These motions could be excited by ordinary gravity waves (as defined in Part II – Figure 2.24). The motions in this frequency range are not affected by the presence of ShoreTension. In the bottom figure of Figure 4.27, it can be seen that the natural frequencies for the sway motion are different than for surge, and that the ShoreTension system has a different (reduced) effect on the reduction of the motions.



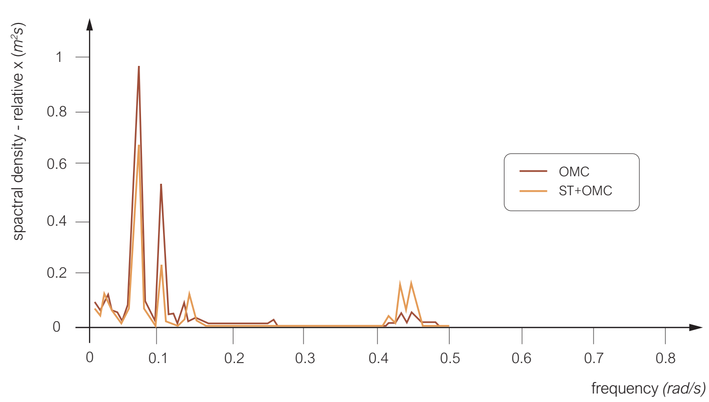


Figure 4.27: Spectral density of relative surge (top) and sway (bottom) (reworked from Vreeburg, 2015, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

A DMA is executed to indicate possible problems due to (large) motions, and to evaluate the effectiveness of the measures that are considered to reduce these motions. For the ShoreTension example it can be seen that it is well capable of reducing the motions near the natural frequency, caused by low frequent excitation such as wind, long waves, or passing ships, but for other types of motions, other measures need to be considered in order to improve the workability.

5 Performance of port and waterway systems

5.1 Energy consumption and emissions by IWT vessels

In Part I – Section 2.1.1 the emerging energy transition was discussed as an important trigger of change. It should be regarded in the context of the 2015 Paris Agreement: the first universal, legally binding climate agreement. It aims to limit global warming, and one of the key elements is to reduce emissions worldwide (European Commission, 2021). As a contribution to this agreement, participating countries had to deliver national climate action plans. The aforementioned IMO restrictions to the sulphur and nitrogen content of fuel are an international example. In 2019, the Netherlands established their national climate agreement with ambitious emission reduction goals (Min. EZK, 2019).

Following these developments, various economic sectors are pressed to reduce emissions, also the IWT sector. To respond to this pressure a Green Deal has been agreed to by IWT stakeholders (Green Deal, 2019). It defines goals and ambitions for inland shipping for the upcoming years, concerning CO_2- and environmental pollutant emissions. concerning the CO_2 emissions and emissions of environmental pollutants. The main aims and objectives are (see also Figure 5.1).

- *2024* – A reduction of CO_2 emissions of at least 20% compared to 2015, and a reduction of environmental pollutants of at least 10% compared to 2015.
- *2030* – A reduction of CO_2 emissions of 40% to 50% compared to 2015;
- *2035* – A reduction of environmental pollutants of 35% to 50% compared to 2015;
- *2050* – Emission-free and climate-neutral inland shipping achieved.

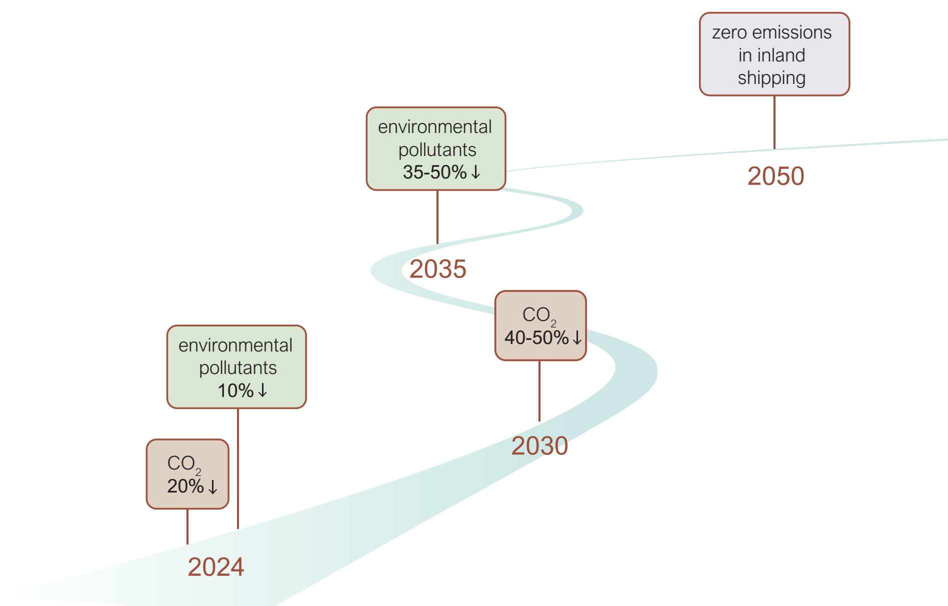


Figure 5.1: Time line Green Deal – goals and ambitions for inland shipping (image modified from Segers, 2021, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

To meet these goals numerous task groups and studies have been initiated to investigate which alternative energy carriers are most promising, what requirements these energy carriers pose for the bunkering infrastructure and what packages of policy measures are likely to be most effective. For each of these and many other similar questions a detailed insight into the current and potential future energy consumption and associated emissions is crucial.

According to CBS (2021b) the total Dutch transport sector was responsible for approximately 12% of all Greenhouse Gas (GHG) emission by the Dutch economy. Within the transport sector 45% of emissions is caused by aviation, 30% by transport over water (sea and inland shipping) and 21% by road transport. The remaining 4% is attributed to transport related services. Two thirds of those emissions take place outside the Netherlands, viz. international aviation and shipping. According to CBS (2021a) IWT inside the Netherlands emitted in 2019 1.94 mln kg CO_2, 25.3 mln kg NO_x and 0.82 mln kg PM10.

To facilitate rational decision making more insight in emission sources is needed than is provided by the aggregated figures discussed above. Various methods to estimate the energy consumption and the associated emissions of an individual IWT-vessel have already been published, i.e. Bolt (2003); Hekkenberg (2012); Vehmeijer (2019); Rijkswaterstaat (2021) and many more.

What all methods including the one described below have in common is that they start with estimating the resistance a vessel experiences when sailing at a given speed. The older methods rely on more simple vessel resistance equations and hydrodynamic effects around the vessels. See Part III – Section 4.5. The estimated resistance is translated to engine power requirements through a number of empirical loss factors. This required engine power can then be used to estimate the required energy for a given time interval. Based on empirical data one can estimate the amount of fuel that is needed to deliver this energy. Depending on the selected fuel type and some additional information such as installed power and engine age an estimate can be made of associated potential for emission. NB: the addition of 'potential' is important to notice, since on-board measures may be implemented to scrub or filter out these emissions before they are in actually emitted, albeit to additional cost.

Below we describe a methodology that is largely in line with the common practice to estimate energy consumption and emissions, with the particular addition that energy consumption and emissions for an individual vessel will be calculated and logged as a function of time and space. Furthermore we add empirical relations to translate the estimated energy consumption to emissions of interest, viz. CO_2, NO_x and PM10. These are useful additions when one is interested in network performance, and to adhere to current QSCs and reference values or targets. By applying the methodology to a representative selection of vessels making representative trips on the transport network, it becomes possible to make bottom-up estimates of energy consumption and emission patterns. This in turn allows for the inter-comparison of policy measures and investment strategies.

Figure 5.2 describes the components of the methodology we will discuss. The method is based on work by Segers (2021). Starting point of the analysis are the ship dimensions (length (L_s), beam (B_s) and draught (D_s)), the sailing speed of the vessel (V_s), and the waterway characteristics (water depth (h_0), ambient current (U_c)). With this information we can estimate the total resistance (kN) a vessel experiences while sailing at a given velocity with respect to the water.

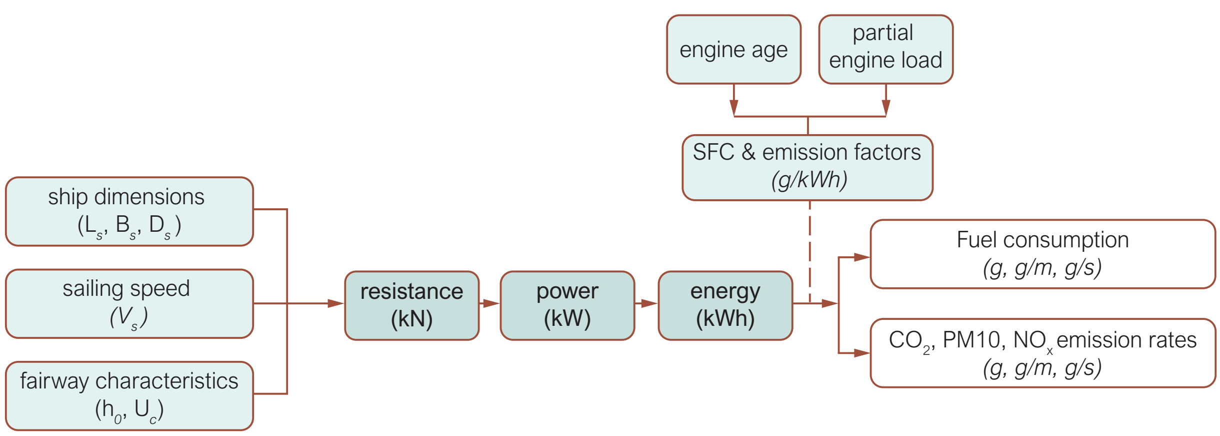


Figure 5.2: Methodology for estimating emissions for IWT vessels (image modified from Segers, 2021, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Once the total resistance (kN) is calculated we estimate the power (kW) that is required to overcome this resistance. We provide estimates of the Effective Horse Power (EHP), the Delivered Horse Power (DHP) and ultimately the Brake Horse Power (BHP) by applying a number of efficiency factors. The total required power can further be subdivided into the power required for propulsion and the power needed for hotel systems on board.

Once the total required power is 'known' we can calculate the energy (kWh) that is consumed by multiplying the total power with the duration of its application. The energy consumption estimate can then be translated to emissions based on empirical relations between energy use and fuel consumption, and fuel consumption and emissions.

Below we treat each substep briefly. For more detail we refer to Segers (2021).

5.1.1 Resistance

For the calculation of the total resistance (R_T) a vessel experiences we use the approach suggested by Holtrop and Mennen (1982). They estimate the total resistance, R_T, from a range of components.

$$R_T = R_f(1 + k_1) + R_w + R_{app} + R_{res} \tag{5.1}$$

In which:

R_T	=	total resistance of the ship $[kN]$,
R_f	=	frictional resistance $[kN]$,
$1 + k_1$	=	form factor of the hull [-],
R_w	=	wave resistance $[kN]$, and
R_{app}	=	appendage resistance $[kN]$,
R_{res}	=	residual resistance $[kN]$.

Frictional resistance including the hull form factor: $R_f(1 + k_1)$

The general way to calculate the drag of an object is by multiplying the dynamic pressure of the fluid by a dimensionless drag coefficient and a surface area. As we have seen in Part III – Section 4.5, the frictional resistance of a vessel follows from

$$R_f = \frac{1}{2}\rho_w V_s^2 \cdot C_f \cdot S \tag{5.2}$$

in which:

$\frac{1}{2}\rho_w V_s^2$	=	dynamic pressure of the fluid $[N/m^2]$,
C_f	=	friction coefficient [-], and
S	=	wetted surface area of the hull $[m^2]$.

As the frictional resistance constitutes a large part of the total resistance, it makes sense to approximate the friction coefficient and the wetted surface area as accurately as possible.

In deep water ($h_0/L_s > 1$), the friction coefficient for a body with a smooth flat bottom and no friction on the sides depends only on the Reynolds number. Zeng et al. (2018) derive on the basis of CFD-model computations:

$$C_{f,\text{ deep}} = \frac{0.08169}{(\log R_e - 1.717)^2} \tag{5.3}$$

in which $Re = V_s L_s/\nu$, with ν the kinematic viscosity $[m^2/s]$ ($\approx 1 \cdot 10^{-6}$). In shallow water ($h_0/L_s < 1$), however, other parameters come into play. Again on the basis of CFD-model computations Zeng et al. (2018) derive:

$$C_{f,\text{ shallow}} = \frac{0.08169}{(\log R_e - 1.717)^2}\left[1 + \frac{0.003998}{\log R_e - 4.393}\left(\frac{h_0 - z - D_s}{L_s}\right)^{-1.083}\right] \tag{5.4}$$

in which h_0 is the undisturbed water depth, z is the maximum water level depression and D_s is the draught of the ship. When taking the friction at the submerged flanks of the ship into account, this becomes:

$$C_f = C_{f0} + (C_{f,\text{ shallow}} - C_{f,\text{ Katsui}}) \frac{S_B}{S} \left(\frac{V_s + \Delta V}{V_s} \right)^2 \tag{5.5}$$

In which:

C_{f0}	=	frictional resistance according to the ITTC-1957 curve [-]; see Equation 5.6,
$C_{f,\text{ Katsui}}$	=	Katsui's friction coefficient for a flat plate in unrestricted water [-]; see Equation 5.7,
S_B	=	area of the flat bottom $[m^2]$,
V_s	=	relative free stream velocity $[m/s]$, or the ships speed (V_s' in case of ambient current), and
$V_s + \Delta V$	=	velocity underneath ship's bottom $[m/s]$ ($V_s' + \Delta V$ in case of ambient current); see Equation 5.11 and Equation 5.14.

Following in-depth discussions the ITTC (1957) agreed on the following frictional resistance curve (ITTC, 2002):

$$C_{f0} = \frac{0.075}{(\log Re - 2)^2} \tag{5.6}$$

Katsui et al. (2005) proposed a friction coefficient for a smooth flat plate in deep water:

$$C_{f,\text{ Katsui}} = \frac{0.0066577}{(\log Re - 4.3762)^a} \tag{5.7}$$

where $a = 0.042612 \log Re + 0.56725$.

The area of the flat bottom, S_B, is estimated by taking $L_s \cdot B_s$. For the wetted surface area of the hull Holtrop and Mennen (1982) give the following empirical formula:

$$S = L_s(2D_s + B_s)\sqrt{C_M} \left[0.453 + 0.4425C_B - 0.2862C_M - 0.003467\frac{B_s}{D_s} + 0.3696C_{WP} \right] + 2.38\frac{A_{BT}}{C_B} \tag{5.8}$$

In which:

L_s	=	the ship's length $[m]$ at the waterline,
D_s	=	draught $[m]$,
B_s	=	beam $[m]$,
C_M	=	midship section coefficient [-],
C_B	=	block coefficient [-] on the basis of the waterline length,
C_{WP}	=	water plane area coefficient [-], and
A_{BT}	=	cross-sectional area of the bulb at still water level $[m^2]$.

The block coefficient is relatively high for inland vessels. For now we assume it to be constant at 0.85; this is the maximum value for which the method of Holtrop and Mennen (1982) is still applicable. Furthermore, most inland ships do not have a bulb. So we assume $A_{BT} = 0$.

Bertram and Schneekluth (1998) relate both C_M and C_{WP} to the block coefficient:

$$C_M = 1.006 - 0.0056C_B^{-3.56} \tag{5.9}$$

$$C_{WP} = \frac{1 + 2C_B}{3} \tag{5.10}$$

The velocity underneath the ship's bottom, $V_s + \Delta V$, according to Zeng et al. (2018) can be estimated with:

$$V_s + \Delta V = 0.4277 \cdot V_s \cdot \exp\left(\frac{h_0}{D_s}\right)^{-0.07634} \tag{5.11}$$

The uncertainty of this formula is 2.5% and it is only suitable for $h_0/D_s \leq 4.0$. When $h_0/D_s > 4.0$, $V_s + \Delta V$ is assumed to be equal to V_s. Note that for resistance calculations $V_s + U_r$ according to Schijf (1949) is typically thought too coarse. The value of $V_s + \Delta V$ refers to the actual velocities directly underneath the vessel, which are higher than the cross-section averaged values that follow from Schijf (1949).

Other than Holtrop and Mennen (1982), we use the method proposed by Watson (1998) to calculate the hull form factor $(1 + k_1)$:

$$1 + k_1 = 0.93 + 0.487c_{14}\left(\frac{B_s}{L_s}\right)^{1.068}\left(\frac{D_s}{L_s}\right)^{0.461}\left(\frac{L_s}{L_R}\right)^{0.122}\left(\frac{L^3}{\nabla}\right)^{0.365}(1 - C_P)^{-0.604} \tag{5.12}$$

In which:

c_{14}	=	coefficient accounting for the specific shape of the ship's afterbody, here assumed to be 1 [-],
L_R	=	length parameter $[m]$,
∇	=	the ship's water displacement $[m^3]$, $C_B \cdot L_s \cdot B_s \cdot D_s$, and
C_P	=	C_B/C_M = the so-called prismatic coefficient [-].

According to Holtrop and Mennen (1982) the length parameter L_R can be calculated from:

$$L_R = L_s\left[1 - C_P + \frac{0.06C_P}{4C_P - 1}(19.4C_P - 13.5)\right] \tag{5.13}$$

With these values the hull form factor, $1 + k_1$, can be determined using Equation 5.12, and with it the effect of viscosity on the frictional resistance (Equation 5.2).

Note that for now we assume $C_B = 0.85$, $c_{14} = 1$ and $A_{BT} = 0$.

Wave resistance: R_w

We used Equation 5.11 to estimate the accelerated velocity underneath the ship's bottom to account for shallow water effects in the calculation of friction resistance, R_f. Likewise, limited water depth also has a significant influence on the wave resistance, R_w.

When a vessel starts to approach its critical speed, V_{lim}, the wave resistance increases significantly. Although Schijf's method (see also Part III – Chapter 4) corrects for the channel cross-section, it does not correct for shallow water effects on the currents directly underneath the vessel (Hekkenberg, 2012). Segers (2021) implements the Karpov method (Van Terwisga, 1989) to estimate this velocity increase. The velocity underneath the ship's bottom, $V_s + \Delta V$, for wave resistance can be calculated with:

$$V_s + \Delta V = \frac{V_s}{\alpha^{**}} \tag{5.14}$$

Coefficient α^{**} depends on Fr_h, the Froude number based on the ship's speed and water depth:

$$Fr_h = \frac{V_s}{\sqrt{gh_0}} \tag{5.15}$$

Figure 5.3 shows the estimation of α^{**} based on the Froude number Fr_h for different h_0/D_s ratios. The appropriate value of α^{**} can thus be selected to derive $V_s + \Delta V$ using Equation 5.14. $V_s + \Delta V$ from Equation 5.14 can be used in the wave resistance calculations but also for the other remaining resistance components.

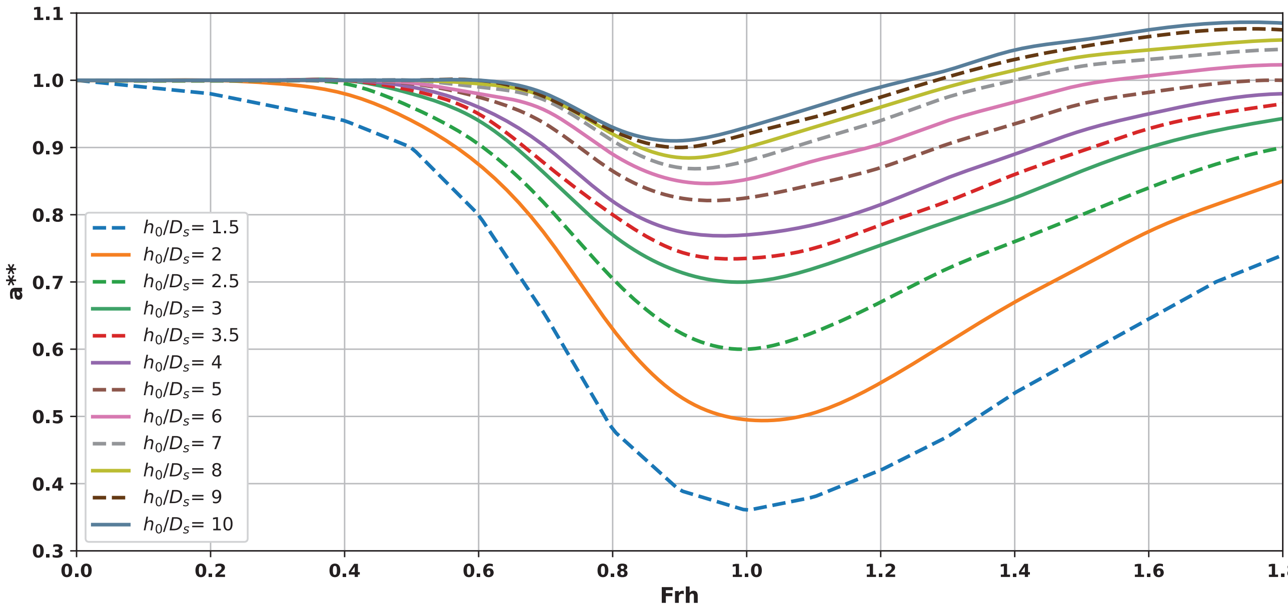


Figure 5.3: Karpov method: estimation of α^{**} based on the Froude number Fr_h for different h_0/D_s ratios (image modified from Segers, 2021, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Holtrop and Mennen (1982) express the wave resistance as

$$R_w = c_1 c_2 c_5 \rho_w g \nabla \exp\left(m_1 Fr_L^d + m_2 \cos\left(\lambda Fr_L^{-2}\right)\right) \tag{5.16}$$

in which:

Fr_L	=	the Froude number based on the ship's speed relative to the water and its length,
c_1	=	an empirical coefficient of proportionality [-],
c_2	=	an empirical coefficient accounting for the reducing effect of the bulbous bow on the wave resistance [-],
c_5	=	an empirical coefficient accounting for the effect of the transom stern (i.e. a flat stern extending to the water line) on the wave resistance [-], and

m_1, m_2, d and λ are empirical parameters.

These quantities can be evaluated according to the rules in Table 5.1, in which

A_T	=	area of the immersed part of the transom stern at zero speed, assumed to be $0.1 \cdot B_s \cdot D_s$,
i_E	=	angle of the waterline at the bow with respect to the central plane,
$D_{s,bow}$	=	draught at the front of the bow, and
h_B	=	position of the centre of the bulb cross-section at the waterline above the keel line, approximately equal to $D_s/2$.

Appendage resistance: R_{app}

The appendages of a ship, such as the rudder, the skeg and the shaft, cause extra resistance, mainly frictional. As the contribution of these terms is relatively small, we will not further elaborate them here. We refer to (Segers, 2021) for further detail.

Quantity	Formula	Condition
c_1	$2223105c_7^{3.78613}(D_s/B_s)^{1.07961}(90-i_E)^{-1.37565}$	
c_7	$0.229577(B_s/L_s)^{0.33333}$	$B_s/L_s<0.11$
	B_s/L_s	$0.11 \leq B_s/L_s \leq 0.25$
	$0.5-0.0625L_s/B_s$	$B_s/L_s>0.25$
i_E	$1+89\exp\left(-\left(\frac{L_s}{B_s}\right)^{0.80856}(1-C_{WP})^{0.30484}\cdots\right.$	
	$\left.\cdots(1-C_p-0.0225\cdot lcb)^{0.6367}\left(\frac{L_R}{B_s}\right)^{0.34574}\left(\frac{100\nabla}{L_s^3}\right)^{0.16302}\right)$	
lcb	$19.4C_p-13.5$	
c_2	$\exp(-1.89\sqrt{c_3})$	
c_3	$0.56A_{BT}^{1.5}/\left[B_sD_s\left(0.31\sqrt{A_{BT}}+D_{s,bow}-h_B\right)\right]$	
c_5	$1-0.8A_T/(B_sD_sC_M)$	
λ	$1.446C_p-0.03L_s/B_s$	$L_s/B_s<12$
	$1.446C_p-0.36$	$L_s/B_s \geq 12$
m_1	$0.0140407\frac{L_s}{D_s}-1.75254\frac{\nabla^{1/3}}{L_s}-4.79323\frac{B_s}{L_s}-c_{16}$	
c_{16}	$8.07981C_p-13.8673C_p^2+6.984388C_p^3$	$C_p<0.80$
	$1.73014-0.7067C_p$	$C_p \geq 0.80$
m_2	$c_{15}C_p^2\exp\left(-0.1Fr_L^{-2}\right)$	
c_{15}	-1.69385	$L_s^3/\nabla<512$
	$-1.69385+\left(\frac{L_s}{\nabla^{1/3}}-8.0\right)/2.36$	$512 \leq L_s^3/\nabla \leq 1727$
	0	$L_s^3/\nabla>1727$
d	-0.9	

Table 5.1: Evaluation of wave resistance parameters (Holtrop and Mennen, 1982).

Residual resistance terms

The residual resistance components are due to the immersed parts of the bulbous bow and the transom stern, and the effect of the hull-roughness and the still-air resistance. The formulations to estimate them, as suggested by Holtrop and Mennen (1982), are of a similar form as the formulation of the frictional resistance, viz. dynamic pressure of the fluid times a friction coefficient times a surface formulation. The cumulative contribution of the residual friction terms can be considerable, but is typically much smaller that the frictional resistance. Since these terms follow the same formulation as the frictional resistance their behaviour is also similar. For further detail on the quantification of this term the reader is referred to Segers (2021).

Relative importance of the resistance terms

In order to get an impression of the relative importance of the various resistance terms, the total resistance and its components have been calculated for an inland vessel according to RWS Class M9 of dimensions 135 × 11.45 × 2.75 m, sailing in water of 10 m depth. Figure 5.4 gives the results as a function of the relative speed. It shows that at higher speeds the wave effects and friction are the major resistance components.

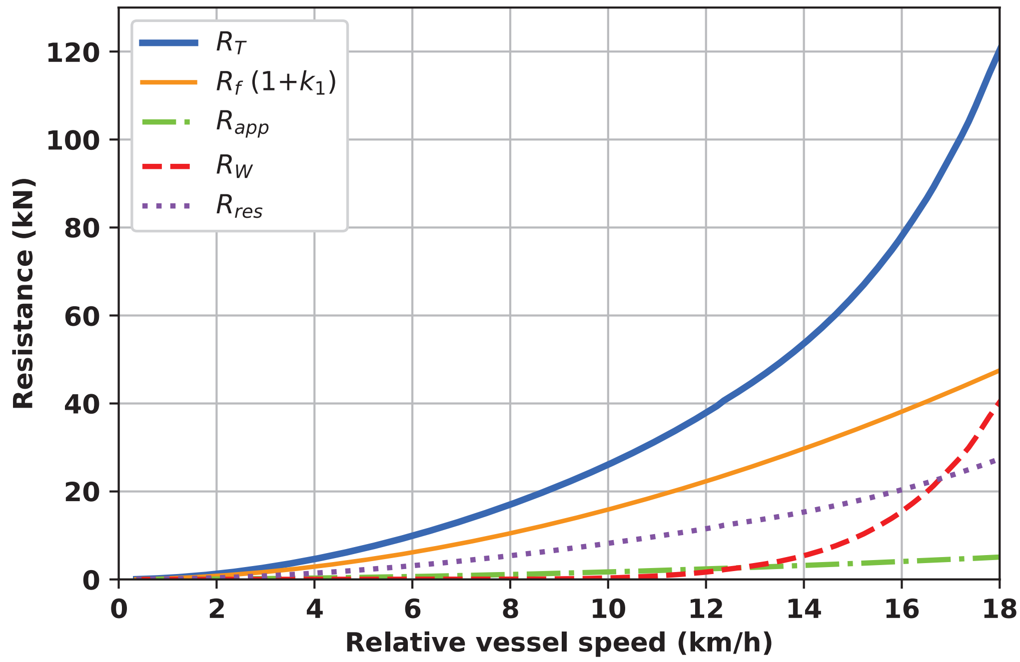


Figure 5.4: Resistance components as a function of the relative vessel speed (h_0 = 7.5 m) (image modified from Segers, 2021, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

In shallow water the resistance is a function of the water depth. Figure 5.5 shows the total resistance, R_T, for the same ship as above, but now for different water depths. The figure clearly shows the depth-dependence with the total resistance drastically increasing for higher velocities at lower water depths.

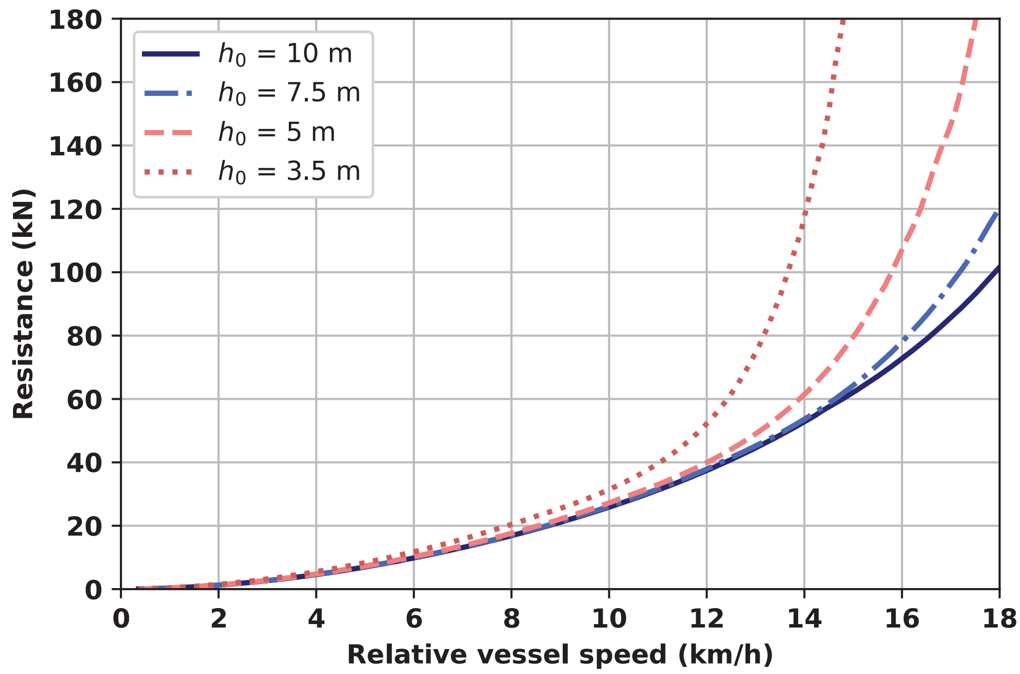


Figure 5.5: Total resistance as a function of the relative vessel speed, for different water depths (image modified from Segers, 2021, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

5.1.2 Power

The previous subsection outlines an approach to quantify the total resistance of a vessel with the ship's dimensions (L_s, B_s and D_s), sailing speed (V_s) and fairway characteristics (h_0 and U_c) as inputs. The next step in the methodology (Figure 5.2) is to estimate the power that is needed to overcome this resistance.

Starting point for this step is the Effective Horse Power (EHP) requirement, which is the work done by the moving vessel. It follows from:

$$P_e = V_s R_T \tag{5.17}$$

In which:

P_e	=	effective power $[kW]$,
V_s	=	ship speed relative to the water $[m/s]$, and
R_T	=	total resistance $[kN]$.

Equation 5.17 can be evaluated now that R_T is known. Since P_e is directly related to the total resistance, R_T, it straightforwardly follows from Figure 5.4 that the required power rapidly increases when a vessel sails faster in the same water depth, and from Figure 5.5 that it rapidly increases when a vessel aims to maintain the same speed as the water gets shallower and the underkeel clearance decreases. The effective power requirement is an important input when designing a ship's power system.

A ship designer has various options for the power generation and distribution system: mechanical, diesel-electric, or a combination of these. Figure 5.6 schematically represents these alternatives. In the mechanical system the Main Propulsion Engine (MPE) is connected to the propeller via a shaft. In the case of a four-stroke engine, which operates at a higher frequency than a two-stroke one, a gear box is required. An additional advantage of such a gear box is that it can couple more than one engine to the shaft. Apart from the MPE, there can be diesel-electric generators on board to generate the power needed for the electric systems on board, the so-called hotel power. Part of the electricity produced can be diverted to the propulsion system through a Power-Take-In (PTI) system. On the other hand, part of the mechanical power produced by the MPE can be diverted to the hotel power through a Power-Take-Off (PTO) system. These facilities enable optimising the power generation system on board. Baldasso et al. (2019) describe a method to do so.

For cargo vessels the hotel power amounts on average to some 8% of the installed power. The other 92% is available for propulsion, but not all power that is generated by the engine is effective due to losses in the transmission system. Figure 5.7 schematically shows such a system for a four-stroke MPE with gearbox in propulsion mode.

The engine power available for propulsion is transferred to the propeller via a transmission system consisting of a gearbox and a shaft with bearings. The energy losses they cause are usually expressed in terms of efficiency

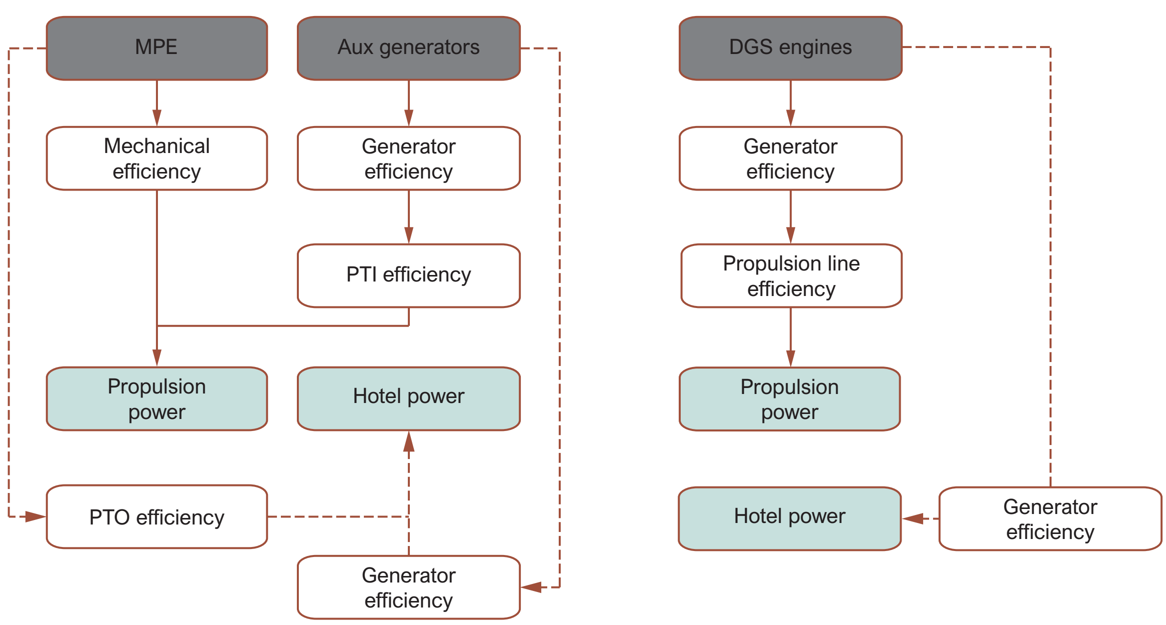


Figure 5.6: Power generation alternatives, left: mechanical system; right: diesel-electric system (image reworked from Baldasso et al., 2019, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0.).

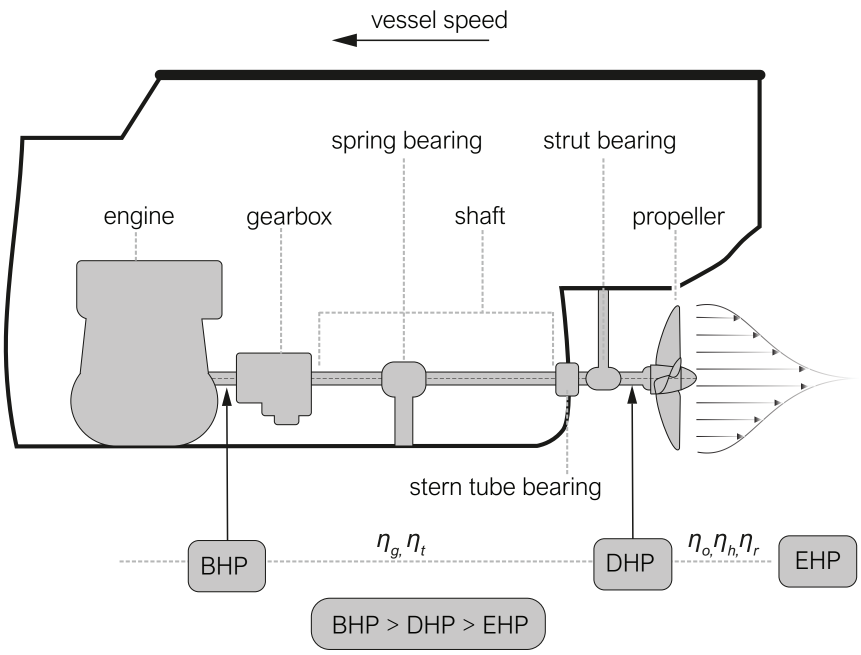


Figure 5.7: Schematization of a ship in propulsion mode, illustrating different power components and efficiencies (image modified from Segers, 2021, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

factors in the relationship between the power for propulsion (Brake Horse Power (BHP)) and the power actually delivered to the propeller (Delivered Horse Power (DHP)):

$$P_d = \eta_g \eta_t P_b \tag{5.18}$$

In which:

P_d	=	delivered horse power $[kW]$,
P_b	=	brake horse power $[kW]$,
η_g	=	gearing efficiency [-], and
η_t	=	transmission efficiency [-].

Commonly used values are 0.96 for the gearing efficiency and 0.98 for the transmission efficiency.

Between the DHP and the EHP that is really available for propulsion there are efficiency losses associated with the hull and the propeller. Hence:

$$P_e = \eta_o \eta_r \eta_h P_d \tag{5.19}$$

In which:

P_e	=	effective horse power $[kW]$,
η_o	=	open water efficiency of the propeller [-],
η_r	=	relative rotative efficiency of the propeller [-], and
η_h	=	hull efficiency [-].

The ***open water efficiency*** of the propeller is the ratio of the thrust power produced by the propeller and the power absorbed by it in open water, i.e. if there is no hull in front of it. Its value depends on the speed of advance and the propeller design and dimensions. Typical values are between 0.55 and 0.70.

The ***relative rotative efficiency*** of the propeller accounts for the variation in water flow to the propeller in the wake behind the ship, as compared with the open water flow conditions. The value of the efficiency factor generally lies close to one (0.98 - 1.02).

The ***hull efficiency*** is determined with the following formula

$$\eta_h = \frac{1-t}{1-w} \tag{5.20}$$

In which:

t	=	thrust deduction factor [-],
w	=	wake fraction [-]

The relative speed of advance of a ship's propeller, V_A, is generally smaller than the speed of the vessel relative to the water, V_s. This effect, which is due to the wake behind the ship, is expressed in the wake fraction coefficient:

$$w = (V_s - V_A)/V_s \tag{5.21}$$

The value of w depends on the shape of the hull, but also on size and location of the propeller. Ships with a large block coefficient have a large wake fraction coefficient, and the water motion around the propeller is very inhomogeneous. For ships with a single propeller, the coefficient lies normally between 0.20 and 0.45. Segers (2021) describes a method to calculate this coefficient, based on an empirical method of Papmel described by Van Terwisga (1989).

The thrust deduction factor is a function of w. In case of a single-screw vessel it reads

$$t = 0.6w(1 + 0.67w) \tag{5.22}$$

for a double-screw vessel:

$$t = 0.8w(1 + 0.25w) \tag{5.23}$$

Equation 5.17, Equation 5.18 and Equation 5.19 and their efficiency factors, reason from the propulsion power towards the effective power. For our methodology we use these equations the other way around to estimate the required engine power for propulsion (BHP) with R_T as a starting point:

$$P_{\text{propulsion}} = P_b = V_s R_T \cdot \frac{1}{\eta_0 \eta_r \eta_h} \cdot \frac{1}{\eta_g \eta_t} \tag{5.24}$$

Beside the propulsion power, there are many other power-consuming systems on board. In order to estimate the hotel power requirements, one may use a load chart (Marine Insight, 2020). Such a chart distinguishes three situations: sailing, manoeuvring and harbour (see Table 5.2 for an example). The power requirements of each electrical system on board is calculated by multiplying the so-called Maximum Rated Power (MRP), i.e. the maximum power the specific device can have, by two factors, viz.

- the load factor LF, which is the ratio of the operational power and the MRP, and
- the utility factor UF, which indicates to what extent the device is used in a particular situation.

In combination with the electrical power needed for propulsion (in case of a diesel-electric engine system) this leads to total generator capacity required.

When vessels become larger, the hotel power component increases. For modern cruise ships, for example, the hotel power may amount to 40% of the total installed power. For IWT-vessels, however, the hotel component is relatively low. For our current methodology we assume that the hotel power amounts to 5% of the installed engine power (cf. De Vos and Van Gils, 2011).

Device	# inst.	# in use	MRP (kW)	Pinst (kW)	Sailing			Manoeuvring			Harbour		
					LF	UF	kW	LF	UF	kW	LF	UF	kW
Steering gear	2	1	24	27	0.8	0.8	17	0.8	0.8	17	0.8	0	0
Windlass	1	1	37	41	0.8	0	0	0.8	0.7	23	0.8	0	0
Baggage crane	2	1	14	16	0.8	0	0	0.8	0	0	0.8	0.6	7.5
Mooring winch	2	1	20	22	0.8	0	0	0.8	0.7	12	0.8	0	0
ER-crane	1	1	4	5	0.8	0.1	0.4	0.8	0	0	0.8	0.2	0.8
Provision davit	2	2	5	6	0.8	0.1	0.9	0.8	0.1	0.9	0.8	0.5	4.7
Galley equipmt	1	1	489	544	0.8	0.2	87	0.8	0.2	87	0.8	0.1	44
Laundry equipmt	1	1	85	95	0.8	0.2	15	0.8	0.2	15	0.8	0	0
Ventilation	1	1	110	122	0.8	0.8	78	0.8	0.8	78	0.8	0.4	39
Side thruster	2	1	250	280	0.8	0	0	0.8	0.7	289	0.8	0	0
Incinerator	1	1	14	17	0.8	0.2	2.6	0.8	0.2	2.6	0.8	0	0
Workshop	1	1	10	11	0.8	0.2	1.8	0.8	0.2	1.8	0.8	0.2	1.8
Welding equipmt	1	1	32	36	0.8	0.1	2.8	0.8	0.1	2.8	0.8	0.1	2.8
Starting air compr.	2	2	9	10	0.8	0.2	3.1	0.8	0.3	4.9	0.8	0.3	4.9
Control air compr.	1	1	3	4	0.8	0.4	1.1	0.8	0.4	1.1	0.8	0.3	1.1
Air drier	1	1	0.3	0.4	0.8	0.4	0.1	0.8	0.4	0.1	0.8	0.3	0.1
Total							**210**			**535**			**107**

Table 5.2: Hotel power load chart (Marine Insight, 2020).

$$P_{\text{hotel}} = 0.05 \cdot P_{\text{installed}} \tag{5.25}$$

Combining Equation 5.24 and Equation 5.25 yields:

$$P_{\text{total}} = P_{\text{propulsion}} + P_{\text{hotel}} \tag{5.26}$$

5.1.3 Energy and emission factors

The previous subsections outlined methods to estimate the total resistance a vessel experiences while sailing at a given speed through a waterway, and the total power that is required to achieve this. The next step in the methodology (Figure 5.2) is to estimate the amount of energy that is involved so that we can make a translation to emissions by using emission factors. This is done in three steps:

1. from total resistance (kN) to total power required (kW),
2. from total power required (kW) and trip duration (Δt) to fuel consumption (kg/kWh), and
3. from fuel consumption (kg/kWh) to emissions (kg) using emission factors.

We will elaborate these steps for diesel fuel.

Step (1)

Making use of Equation 5.1, Equation 5.17 and Equation 5.26 we can estimate the total power requirement as:

$$P_{\text{total}} = P_{\text{hotel}} + \frac{V_s R_T}{\eta_0 \eta_r \eta_h \eta_g \eta_t} \tag{5.27}$$

Step (2)

The fuel consumption to produce this power depends on the vessel (class, engine type, engine age) and the fuel type. The specific energy content of diesel is around 45 MJ/kg, i.e. 12.5 kWh/kg. Not all of this is generated by the engine, due to efficiency losses. The energy production of a diesel engine lies in the range of $4 - 5\ kWh/kg$ fuel, depending on the age of the engine. This means that the amount of diesel needed to produce the total required power for a trip of duration Δt follows from:

$$W_f \approx \epsilon_d \cdot P_{\text{total}} \cdot \Delta t \tag{5.28}$$

in which W_f is the amount of fuel needed to produce the total amount of power for a trip expressed in kg diesel and the factor $\epsilon_d = 0.20 \div 0.25\ kg$ diesel/kWh.

Step (3)

The total emissions of a gas x for a trip of duration Δt can be derived from (Hulskotte and Bolt, 2012):

$$EM_x = EF_x \cdot P_{\text{total}} \cdot \Delta t \tag{5.29}$$

where EF_x is an emission factor for a compound that is present in the fuel used.

Diesel fuel consists of carbon for 86%, which means that the carbon content of diesel fuel is 720 g/l. Combustion to CO_2 adds 1920 g/l of oxygen, so a litre of burnt diesel fuel produces 2640 g CO_2. The specific density of diesel fuel is 0.835 kg/l, so this corresponds with $2.640/0.835 = 3.16\ kg$ CO_2/kg fuel.

This means that on the above trip the total emission amounts to $3.16 \times W_f$ kg CO_2, or $0.00316 \times W_f$ ton CO_2. Assuming $\epsilon_d \approx 0.225$, the emission factor for CO_2 is then

$$EF_{CO_2} = EM_{CO_2}/(P_{\text{total}} \cdot \Delta t) = 3.16 \cdot 10^{-3} W_f/(W_f/\epsilon_d) \approx 7 \cdot 10^{-4} \text{ton CO}_2\text{/kWh} \tag{5.30}$$

Note that this refers to energy produced by the engine, not the total energy content of the fuel. Once the total emissions of gas x for a trip of duration Δt are known, they can be translated to emissions per unit time, per unit distance or per unit cargo to assess network performance.

5.1.4 Emission rates: CO_2, PM10 and NO_x

The previous subsection showed the basic steps involved to go from energy consumption to emissions. For the final step in our methodology (Figure 5.2) it is important to realise that the emission factor, EF_x, is not a constant.

First, it makes a difference what the age of the engine is. Second, the engine usage makes a difference. Segers (2021) addresses the first issue by picking a general emission factor (EF_{general}) from a table, and the second one by implementing a correction factor ($C_{\text{correction}}$) that is related to engine usage:

$$EF_x = EF_{\text{general}} \cdot C_{\text{correction}} \tag{5.31}$$

The x in EF_x can refer to different emission types (e.g CO_2, PM10 and NO_x).

Engine age

The construction year of the engine is likely to affect the general emission factor. Over the years the preference changed from slow to fast running engines. Furthermore, ongoing technological development has resulted in changes in the emission patterns.

Table 5.3 lists data provided by TNO (Ligterink et al., 2019) regarding general emission factors. For each 'engine construction year'-class, a specific fuel consumption is specified, and corresponding general emission factors for CO_2, PM10 and NO_x are given.

By providing a 'construction year class' as input, an emission estimation algorithm can pick the appropriate specific fuel consumption and general emission factors from the table.

Construction year classes	Weight class	Fuel consumption [g/kWh]	CO_2 [g/kWh]	PM10 [g/kWh]	NO_x [g/kWh]
1900 - 1974	L1 – L3	235	746	0.6	10.8
1975 - 1979	L1 – L3	230	730	0.6	10.6
1980 - 1984	L1 – L3	225	714	0.6	10.4
1985 - 1989	L1 – L3	220	698	0.5	10.1
1990 - 1994	L1 – L3	220	698	0.4	10.1
1995 - 2002	L1 – L3	205	650	0.3	9.4
2003 - 2007 CCR-1	L1 – L3	200	635	0.3	9.2
2008 - 2018 CCR-2	L1 – L3	200	635	0.2	7
2019 - 2019 CCR-2	L2 – L3	200	635	0.2	7
2019 - 20xx stage V	L1	205	650	0.1	2.9
2020 - 20xx stage V	L2 and L3	190	603	0.015	2.4

Table 5.3: General emission factors of CO_2, $PM10$ and NO_x for different construction year classes of marine engines (Ligterink et al., 2019).

Partial engine load

Emissions are different in each of the four stages of motion a vessel experiences, viz. stationary, accelerating, steady propulsion and decelerating:

- in the steady propulsion stage a vessels sails at its average operational speed, which is different for every vessel class and for loaded and unloaded sailing;
- in the stationary and deceleration stages, experience shows that the engine takes only about 15% of its maximum power; while
- in the acceleration stage the vessel uses its maximum power.

Engines are less efficient when the partial engine load is low. This results in higher emission factors; more incomplete combustion processes result in higher emission.

To take this effect into account, the general emission factor (see Table 5.3) has to be multiplied by a correction factor (see Figure 5.8) that reflects the additional emission due to partial engine load.

Selecting the appropriate general emission factors based on engine age, and subsequently applying a correction factor related to engine load, accounts for the largest effects that influence the correction factor. With this, our methodology to estimate energy consumption and emissions is complete.

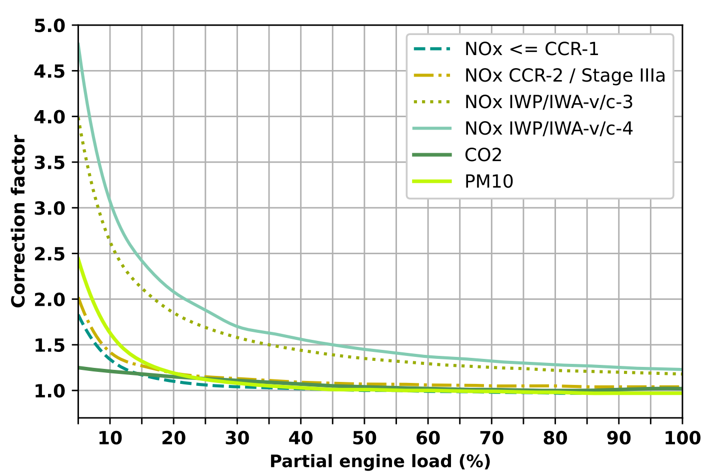


Figure 5.8: Partial engine load factors based on the values from Ligterink et al. (2019) (image modified from Segers, 2021, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

5.1.5 Composite results

In this subsection we show some examples of the behaviour that results from an algorithm that includes all aspects mentioned.

Emissions as a function of vessel speed

As a first example we inspect how the emissions of an M9 vessel, with a given engine age (viz. 1990) and dimensions ($L_s = 135m$, $B_s = 11.45m$, $D_s = 2.75m$), behave as a function of vessel speed on the one hand, and water depth on the other. Figure 5.9 shows the results from applying the algorithm. NB: the emissions are expressed in g/km.

For very low vessel speeds, the engine is not used in its optimal range. Figure 5.8 shows that for lower partial engine loads the correction factor increases dramatically. Furthermore, due to low vessel speeds, the vessel takes longer time to travel a certain distance and thus acculmulates more emissions during that certain distance, which in turn results in a strong increase in the emissions in g/km.

For very high speeds, the resistance will greatly increase. Figure 5.4 illustrates how the wave related resistance in particular, will increase drastically. So even though higher velocities mean that the emissions will be spread out over a larger area, the cumulative effect still results in a strong increase in the emissions in g/km.

On top of these two aspects Figure 5.9 clearly shows the sensitivity of the emissions in g/km to reduced water depths.

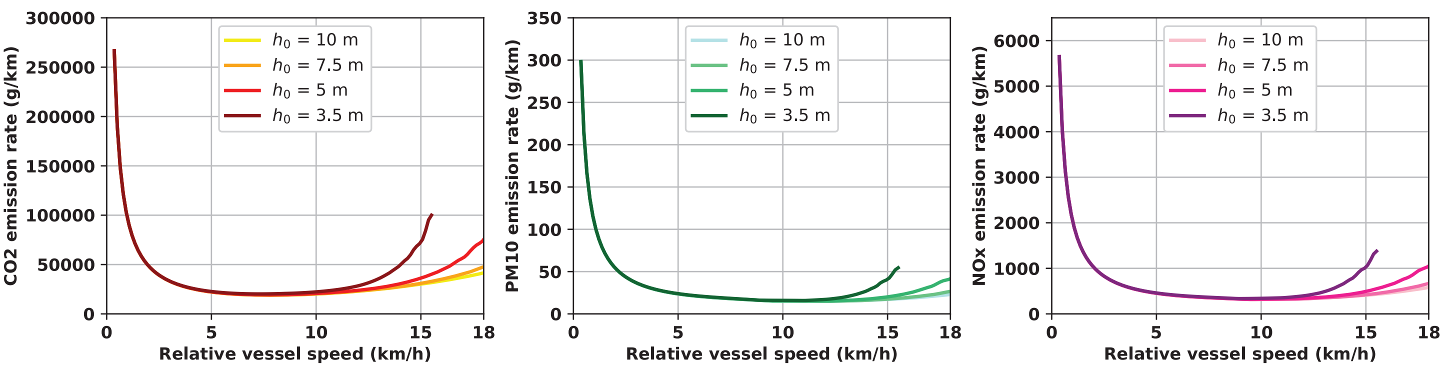


Figure 5.9: Emissions as a function of vessel speed (images modified from Segers, 2021, by TU Delft – Ports and Waterways are licenced under CC BY-NC-SA 4.0).

Emissions as a function of partial engine load

As a second example we inspect how the emissions of an M9 vessel, with given dimensions ($L_s = 135m$, $B_s = 11.45m$, $D_s = 2.75m$) and for a given water depth (viz. $h_0 = 10m$), behave as a function of vessel speed on the one hand, and engine age on the other. Figure 5.10 shows the results from applying the algorithm. NB: the emissions have again been expressed in terms of g/km.

The effect of newer engine ages is clearly visible in the emission rates. Especially for the nitrogen oxides (NO_x) and particulate matter (PM10) a significant difference in the emission rates between older and newer engines can be observed. For PM10, the emission rates drop nearly down to zero for the newest engines.

In summary the following parameters have the largest influence on the emission rates of IWT-vessels. Changes in the amount of installed power particularly affect the particulate matter (PM10) emission rates. Changes in vessel speed have the largest effect on CO_2 emission rates. Changes in the engine age have a significant influence on the nitrogen oxides (NO_x) and particulate matter (PM10) emission rates. Technological innovation has already reduced CO_2 emission rates, so that emission type is less sensitive for engine age. The next section shows how the methodology described above (see Figure 5.2) can be used to analyse network performance.

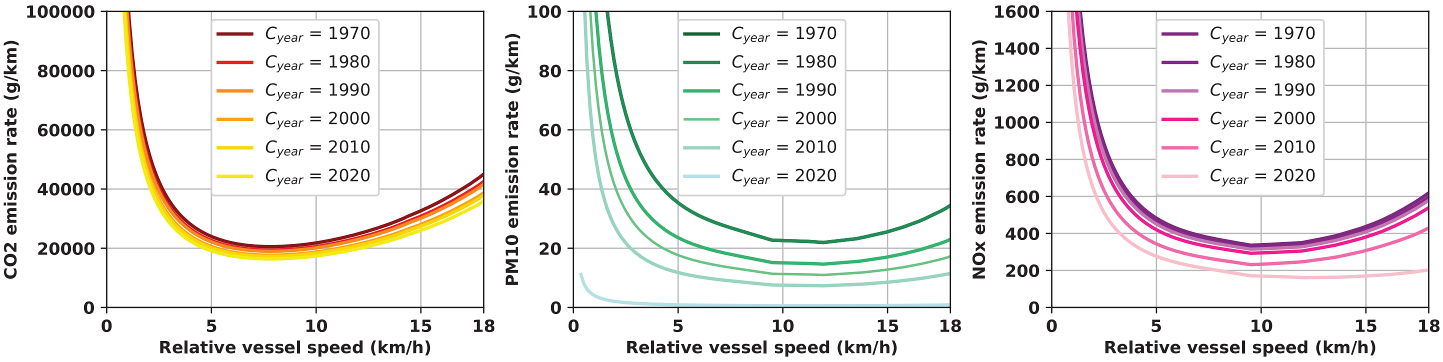


Figure 5.10: Emissions as a function of engine age (images modified from Segers, 2021, by TU Delft – Ports and Waterways are licenced under CC BY-NC-SA 4.0).

5.2 Emission performance of transport corridors

The previous section described a methodology to estimate the energy consumption and associated emissions of an IWT-vessel. The trigger for its development came from emission reduction objectives that followed from the global Paris Agreement and the subsequent more local implementations of it via Green Deals and IMO regulations.

In Frame of Reference (FoR) terms the reduction targets from the Green Deal (2019) can be regarded as operational objectives. The methodology from Section 5.1 can be regarded as a Quantitative State Concept (QSC) that helps to quantify these operational objectives. A logical next step is to apply the methodology to assess network performance. As outlined in Part I – Section 2.2.2 and Chapter 1 of the current Part this requires the definition of indicators, defined as assemblages of QSCs that indicate whether or not there is a problem. In this section we will show how the methodology for energy consumption and emission estimation can be used to investigate the emission performance of a corridor.

5.2.1 Analysis of a single trip

To analyse vessel performance on a network, some basic information should be available that can typically be found in vessel trip logs. Table 5.4 shows the first few lines of a vessel trip log and some basic information it may contain on position and time. In this case each row represents an incremental move event of a vessel. In other cases a log can take the form of a list of consecutive positions and timestamps, but the information is the same.

The first two columns in Table 5.4 indicate the start and stop time of the move, and the second two columns the corresponding geographical coordinates. As indicated underneath the table this information can be used to derive the travelled distance, Δx, and the travel time, Δt. With this the average vessel speed, V_s, during the move event can be derived. Assuming we know the vessel dimensions (L_s, B_s and D_s) and the average waterway characteristics (h_0 and U_c) at the location where the move event took place, we have all the information needed to estimate the total resistance (kN) the vessel experiences and the total energy (kWh) that was consumed during the move event. When, furthermore, we know (or assume) the engine age and the average partial load, we can estimate the total potential emissions of CO_2, PM10 and NO_x that occurred during the move event (see Figure 5.2). By repeating this procedure for each move event in the trip log a vessel's energy consumption and potential emissions can be estimated as a function of space and time.

	time_start	time_stop	edge_start	edge_stop	total_energy	total_emission_CO2	total_emission_PM10	total_emission_NOX
0	2020-09-26 00:00:00.000000	2020-09-26 00:01:37.988698	POINT (4.40878376619477 51.6893044653478)	POINT (4.407711423268813 51.68872877120878)	1.028666	797.232566	0.379078	11.358754
1	2020-09-26 00:01:37.988698	2020-09-26 00:01:46.039699	POINT (4.407711423268813 51.68872877120878)	POINT (4.407623317192122 51.68868147089958)	0.084518	65.502657	0.031146	0.933264
2	2020-09-26 00:01:46.039699	2020-09-26 00:04:00.501781	POINT (4.407623317192122 51.68868147089958)	POINT (4.40615183993005 51.6878914989466)	1.411557	1093.978722	0.520178	15.586713
3	2020-09-26 00:04:00.501781	2020-09-26 00:23:56.405478	POINT (4.40615183993005 51.6878914989466)	POINT (4.3925552967856 51.6812504548851)	12.554364	9729.829984	4.626459	138.627991
4	2020-09-26 00:23:56.405478	2020-09-26 00:24:52.273815	POINT (4.3925552967856 51.6812504548851)	POINT (4.39198470467551 51.6808950327794)	0.586495	454.542805	0.216132	6.476203

Δt Δx $V_s = \Delta x / \Delta t \rightarrow P_{tot} \rightarrow E_{tot} \rightarrow$ Emissions

Table 5.4: Vessel log: input for energy consumption and emission calculations (table by Segers, 2021, is licenced under CC BY-NC-SA 4.0).

It is good to realise that an actual trip log, in terms of information on position and time, does not differ too much from a simulated trip log. This means that the methodology can be applied to both measured and simulation trip log data. NB: there will be some differences in resolution as we will see in the next subsections.

A well-known vessel tracking system is the Automatic Identification System (AIS) that collects specific data that vessels transmit via on-board transceivers and makes it available to waterway users and Vessel Traffic Service (VTS)-operators to promote safe navigation. AIS logs are lists of consecutive positions and timestamps, and often contain additional information such as the IMO identification number, the ship name, the ship type, the ships basic dimensions, draught, etc. Note that some of the additional information has to be submitted manually, and as a consequence is not very reliable, but position and time are not manual inputs. Rather these are values derived automatically from the ship's Global Positioning System (GPS). As such they are considered quite reliable (even though this data may contain outliers depending on environmental conditions). An alternative source for measured data may be the ship's own on-board logging system.

Simulation models, as described in Section 2.6 (i.e. OpenTNSim, OpenCLSim), also produce vessel trip logs as output. Before the simulation starts, the modeller needs to provide input on vessel dimensions and waterway properties to drive the simulation. As a consequence, the information to apply the methodology described above is also available.

As can be seen in Table 5.4 the energy consumption and emissions can be estimated and added to the log for each move event. These 'enhanced' logs can then be used for analysis. Deriving the trip totals is a simple matter of addition. More interesting is the fact that energy consumption and emissions can now be 'known' in space and time. Network performance can now be analysed by adding the results of all trips for a given day, for example or all emissions on a specific stretch of the network. The next subsection provides examples of this.

5.2.2 Analysis of a representative set of trips

In response to a question by Rijkswaterstaat, Segers (2021) developed the methodology described in Section 5.1. To analyse its performance she applied the methodology to the busiest part of the Dutch IWT network: the Rotterdam–Antwerp corridor (see Figure 5.11).

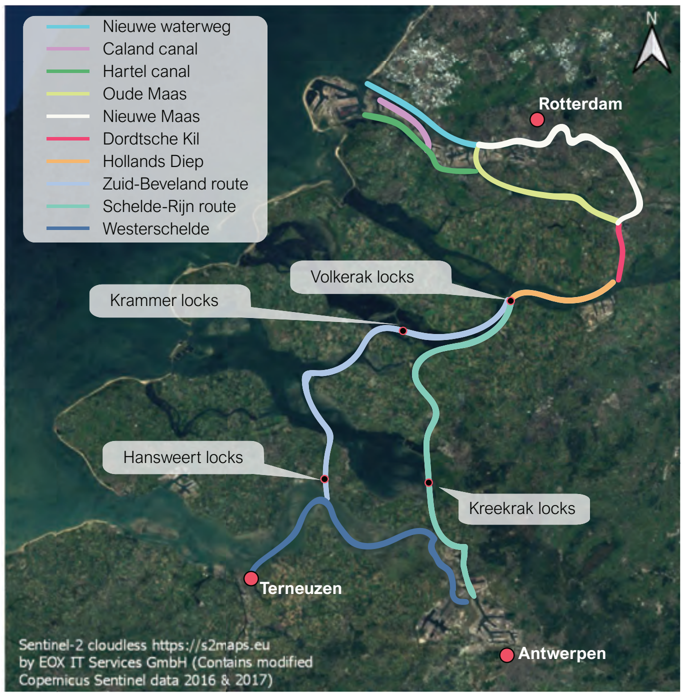


Figure 5.11: The Rotterdam-Antwerp corridor (image modified from Segers, 2021, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

AIS data

A starting point for the analysis of Rotterdam-Antwerp corridor emissions, based on AIS data, is to first look at the traffic intensity. Figure 5.12 shows the number of vessels counted on the network's key waterway sections, for September 2nd, 2019.

Figure 5.12: Traffic intensity as derived from AIS for the Rotterdam-Antwerp corridor for September 2nd, 2019 (image modified from Segers, 2021, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

Figure 5.13 shows the resulting heatmaps for CO_2, PM10 and NO_x, for September 2nd, 2019, based on individual vessel trips. NB: the figures show the cumulative emission 'potentials' for IWT-vessels for a specific day.

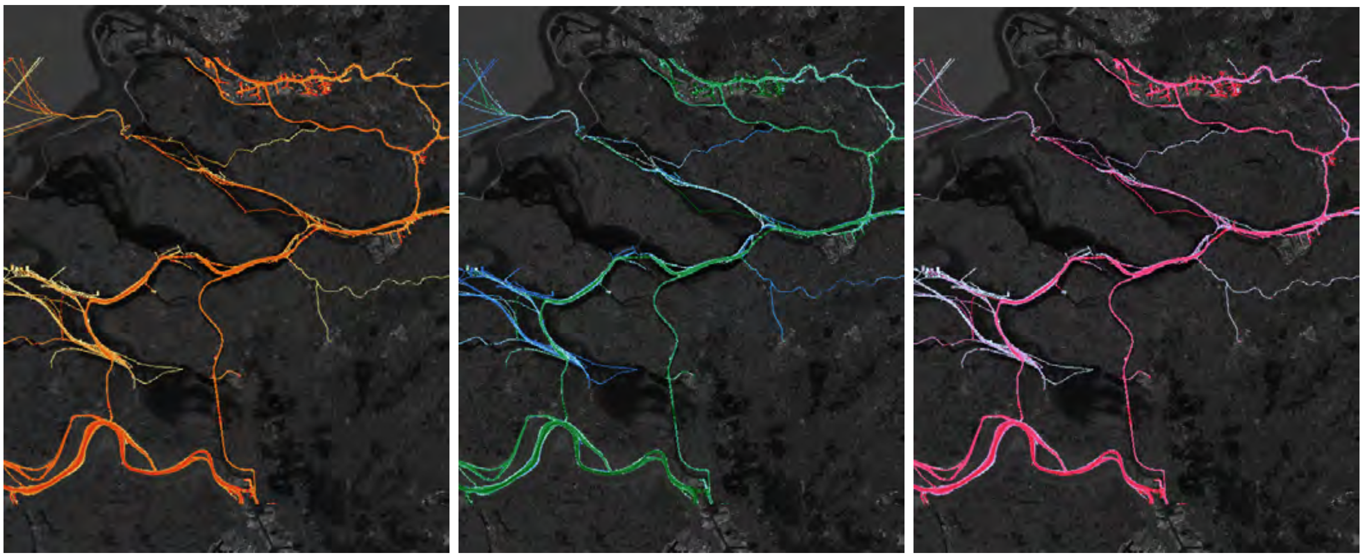


Figure 5.13: Heatmaps for potential CO_2, PM10 and NO_x emissions, for September 2nd, 2019, based on AIS data directly (images by Segers, 2021, are licenced under CC BY-NC-SA 4.0).

Despite the fact that the subfigures in Figure 5.13 look interesting at first glance, there are limitations to their practical use. Ideally one would want to aggregate the emission heatmaps and attribute the summed emissions to the specific elements of the transport graph. Figure 5.14 shows that (potential) emissions are not uniformly distributed over the network. Rather there are areas with higher emission potentials (corresponding with the busier parts of the network) i.e. apparent emission potential hotspots. These hotspots are associated with the presence of locks (see Figure 5.11). At these locations vessels sail slowly, or lie stationary for a period of time. Lower vessel speeds mean less energy consumption per unit time, so lower emissions. This reduction, however, is counter balanced by lower partial engine loads, which in turn increases emissions. When the vessels lie still, e.g. in the lock waiting area or during levelling, the engine is idling and only hotel power is used. While in such cases the emissions per unit time may be low, emissions per unit space will increase due to local accumulation.

Figure 5.14: Potential CO_2, PM10 and NO_x emissions, for September 2nd, 2019, based on AIS data, projected on the transport network (images by Segers, 2021, are licenced under CC BY-NC-SA 4.0).

OpenTNSim simulation data

Now that we have the basic information on potential emissions based on AIS data, a next step is to simulate a similar traffic pattern using OpenTNSim. For this, Segers (2021) analysed the AIS data to create an Origin-Destination matrix based on the data of September 2nd, 2019. By running a simulation for the same date, using the Origin-Destination matrix, averaged vessel speeds and an assumed distribution of engine ages in the fleet as input, a quite encouraging match between the two results can be found (see Figure 5.15).

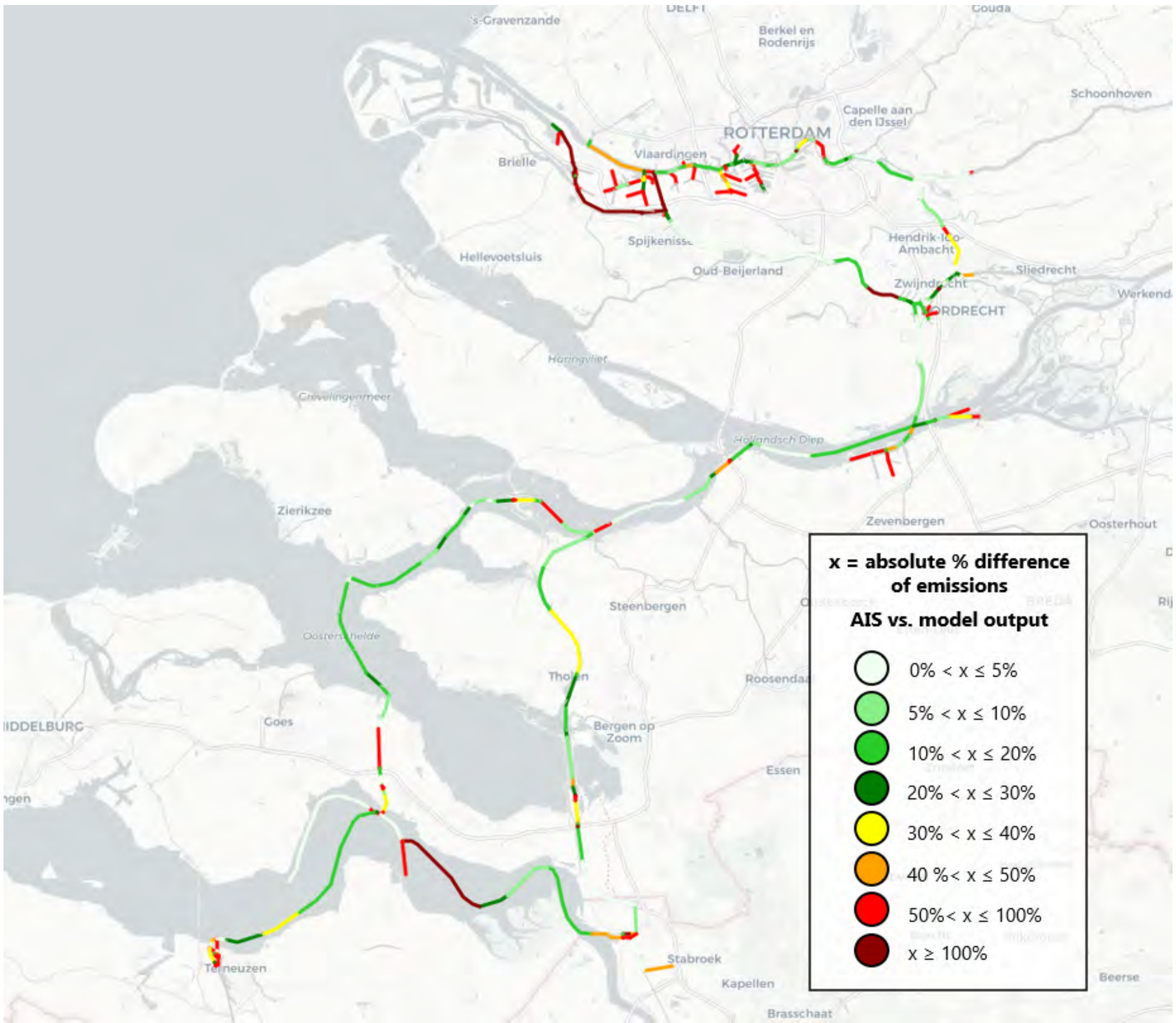


Figure 5.15: Comparison of the results based on AIS data with the results derived from OpenTNSim simulations (image by Segers, 2021, is licenced under CC BY-NC-SA 4.0).

Obviously there are still differences between the 'measured' and 'modelled' results, but by and large differences are smaller than 20% and for large stretches of the network even smaller than 10%. The main cause of these differences, for now, is that the AIS data provides a lot of detail on accelerations and decelerations over the network, while the simulation uses an averaged speed for the entire trip from origin to destination. Since the effect of sailing speed on frictional resistance responds quadratically (see Equation 5.2) and additional effects can be expected in shallower water, these differences between average and actual speed may lead to significant local differences. But the comparison is encouraging nonetheless. The analysis also allows us to inspect estimated totals, which shows a similar result (see Table 5.5).

	AIS t0 emission scenario	**Model simulation t0**	**Difference**
Average fuel consumption [L/h]	110	119	8.2%
Average required power [kW]	446	482	8.1%
Total fuel consumption [L]	545,868	530,730	-2.8%
Total CO_2 emission [kg]	1,551,610	1,547,533	-0.3%
Total PM10 emission [kg]	712.61	685.86	-3.8%
Total NO_x emission [kg]	19,966	19,546	-2.1%

Table 5.5: Output of AIS 't0 emission scenario', compared to model simulation output: Average fuel consumption and power; Total fuel consumption and potential emissions of one day (2 Sept 2019) (Segers, 2021).

Next to the relative differences between ‘measured’ and ‘modelled’ results, it is also good to note that there will be differences between theory and practice in terms of the absolute numbers. The AIS data was filtered to only include cargo vessels and assumptions were made about installed power and engine age. Furthermore, assumptions were made on water depths, based on a combination of highly detailed bed information with much coarser water level information. Next, we know that parts of the Rotterdam-Antwerp corridor experience currents, either of river discharge origin, or tidal origin. While currents can straightforwardly be incorporated in the methodology, actually acquiring this information for all parts of the network as a function of time can be quite a challenge. For this reason this aspect was not yet included by (Segers, 2021) and is further research is recommended.

Comparison of measures

The ability to estimate a t_0 state based on AIS data is an encouraging step forward en route to the development of energy consumption and emission-related network performance indicators. A next step would be to define time intervals and traffic patterns to determine a desired or reference state.

Another encouraging result is that there is a reasonable agreement between the measured and simulated t_0, certainly in terms of averages. This allows policy analysts to test and compare various emission reduction packages.

(Segers, 2021) showed how this could work for a number of measures, viz. an engine renewal policy and sailing speed limitations. (Vehmeijer, 2019), using a slightly different quantification method, looked at the potential effects of modifying the network with higher bridges or the conversion of a sluice to a lock, both interventions influence the sailing distance and emissions.

5.3 Multi-modal corridor analysis

Section 5.1 describes how to quantify one specific aspect of transport over water, i.c. the energy consumption and associated emission patterns of IWT vessels. Section 5.2 shows how to extrapolate this to fleet performance on a given corridor, and to the assessment of alternative emission-reducing measures. A next level of complexity is to study the multi-modal performance of corridors.

5.3.1 A case study: Myanmar

A private developer intends to develop an industrial estate along the Ayeyarwady River near Mandalay City, about 900km upstream from Yangon, the main sea port in Myanmar. IWT over the Ayeyarwady River has traditionally been the preferred mode of transport in Myanmar, from ancient times to more recent years. In the first decades of the 20th century, the Irrawaddy Flotilla Company (IFC) was the largest IWT company in the world, owning over 600 vessels carrying more than 6 million passengers and more than 1 million ton of cargo. More recently however, investments in roads have improved transport by truck and cars. Passenger traffic by boat has declined and long-distance passenger travel has totally disappeared. The basic questions to be answered are:

- which types of cargo can be attracted by the river port,
- what volumes of cargo can be attracted by the river port, and
- at what tariff can the goods be handled at the port, providing a profitable business whilst remaining a competitive mode of transport?

Step 1: Market Study - Trade flows. Demand and Supply

As a first step of the studies (RHDHV, 2015), Origin - Destination matrices were compiled, showing what types of cargo at what volumes are currently transported from/to the wider Mandalay Region (Figure 5.16). The cargoes were split into main commodities, e.g. various dry bulk, agricultural and timber products. The volumes are based on interviews or surveys with existing cargo transporters and available country statistics. Future volumes of cargo are based on economic forecasts and information of major (industrial) developments taking place in the region, e.g. in the mining sectors, industrial estates and general trends in developing economies.

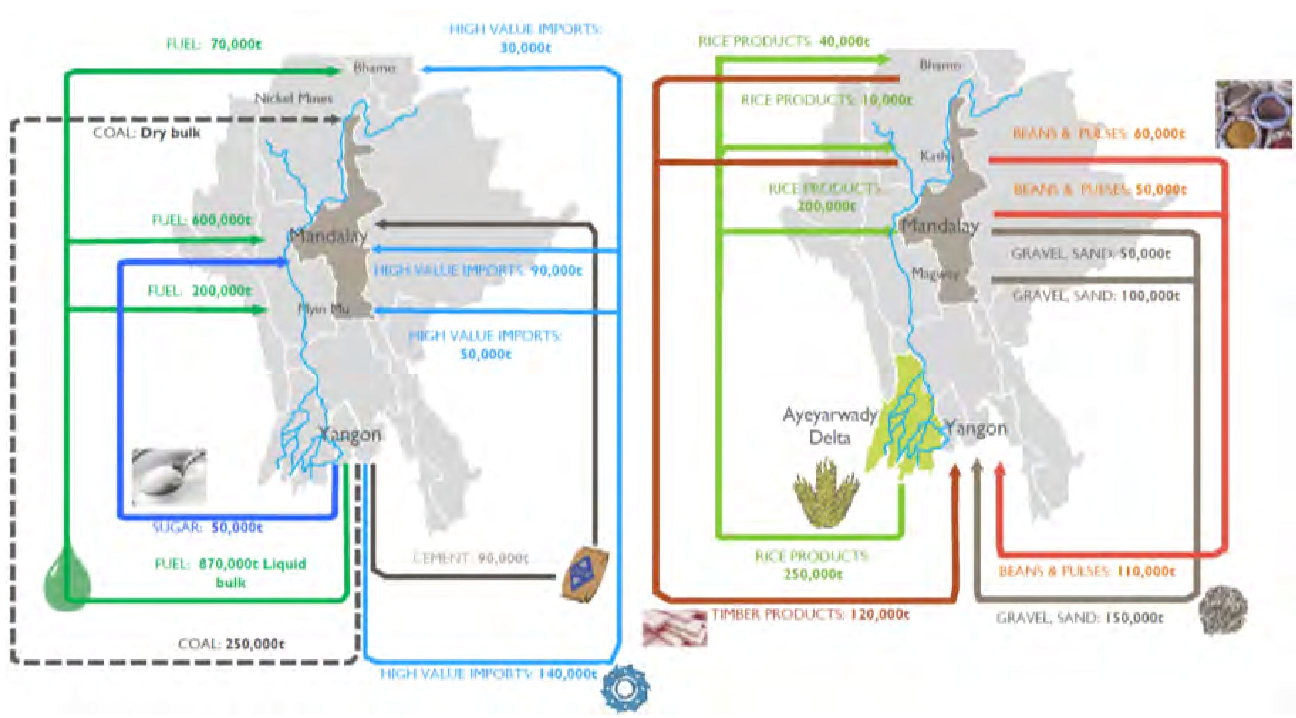


Figure 5.16: Analysis of origins and destinations for various types of cargo (for illustrative pruposes only) (by Royal HaskoningDHV is licensed under CC BY-NC-SA 4.0).

Table 5.6 presents the cargo currently transported by river transport from/to various cities along the Ayeyarwady River. A river port near Mandalay would be able to capture cargo destined for or originating from Mandalay, but also provide transhipment services for cargo from/to upstream ports using smaller (500t) vessels.

RIVER PORT THROUGHPUT (TONNE/ANNUM)

Name	Yangon	Irrawaddy Delta	Magway	Nyaung U	Pakokku	Myin Mu	Mandalay	Katha	Mines	Bhamo	Total
Vessel size (DWT)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	500	500	500	
Import	450,000	0	30,000	70,000	30,000	170,000	1,020,000	40,000	250,000	130,000	2,180,000
Export	1,350,000	280,000	30,000	20,000	40,000	10,000	210,000	30,000	20,000	120,000	2,180,000
Annual Throughput	1,800,000	250000	50,000	80,000	50,000	190,000	1,180,000	130,000	270,000	250,000	4,3700,00

Table 5.6: Cargo transported by river transport from/to various cities along the Ayeyarwady River (for illustrative pruposes only) (by Royal HaskoningDHV is licensed under CC BY-NC-SA 4.0).

In addition to the existing cargo flows over the river, it was recognized that new businesses on the industrial estate will attract large volumes of cargo. The demand for fuel products in central and northern Myanmar has risen sharply over the last decade and therefore fuel storage shows good potential. Several private developers have shown interest in collaboration to develop such a storage facility within the port. This may attract considerable cargoes.

Step 2: Mapping of available transport corridors & modes of transport

The existing and future cargo flows can be transported by barge, rail and road. Liquid bulk (oil products) can be transported by pipeline. All available transport means from the main origins and destinations where mapped (see Figure 5.17), including travel distances and any development which may take place in the coming years and decades, such as road improvement, river improvement projects or railway extensions.

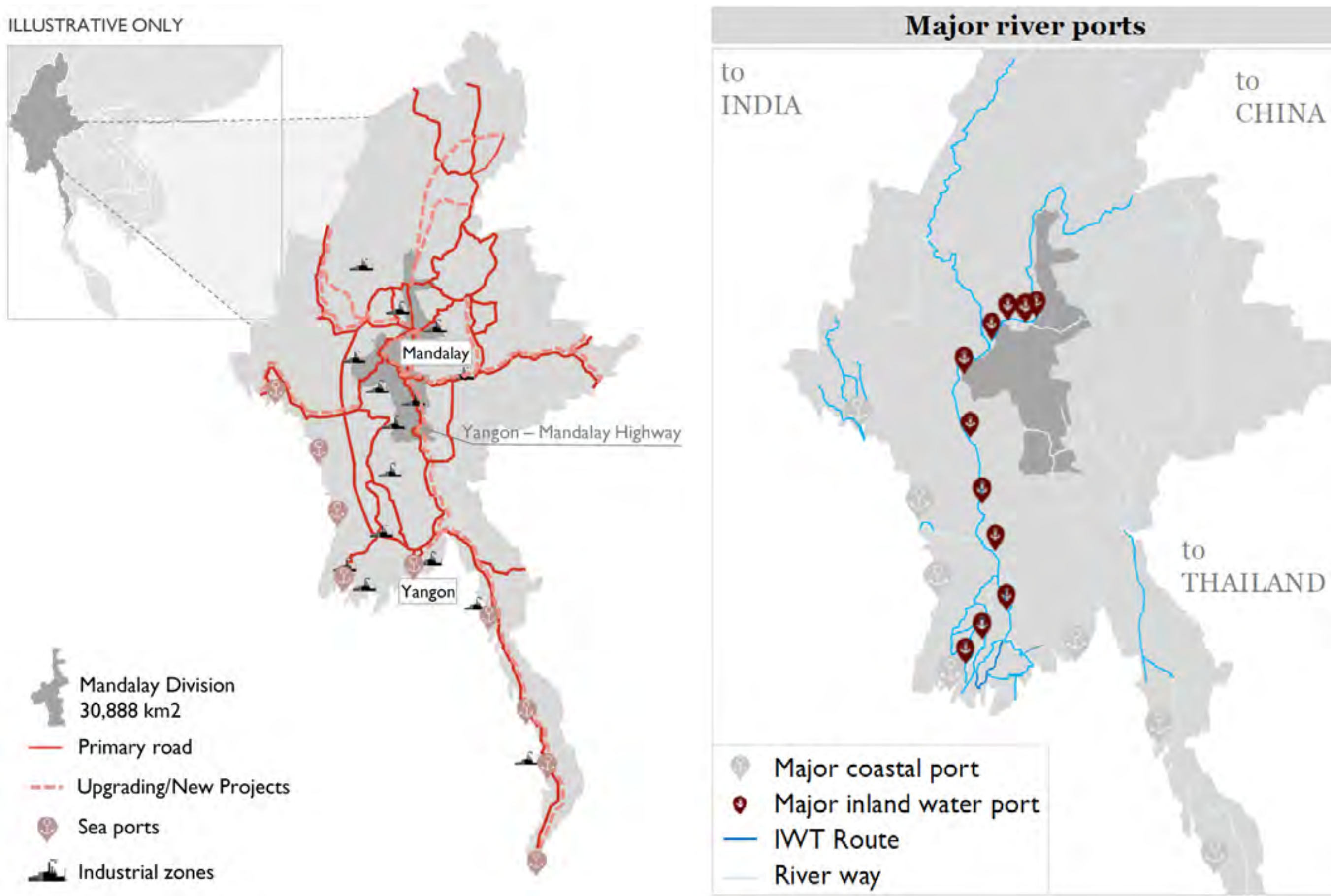


Figure 5.17: Analysis of origins and destinations for various types of cargo (for illustrative pruposes only) (by Royal HaskoningDHV is licensed under CC BY-NC-SA 4.0).

Step 3: Intermodal competition

When cargo owners decide to ship cargo to a given destination, they will have to decide which mode of transport to use based on a) costs, b) time and c) reliability. Some examples of how these three factors can influence their choice are:

- Agricultural goods are perishable. Fast transport is required. This is more evident for fruits than for dried products, such as rice or dried beans. The value of the product will decrease with time, hence transport costs can be higher, provided goods will be delivered more quickly.
- Demand for cement for the construction industry is relatively predictable and may depend on planned projects. Delivery within foreseeable time and having some storage allows the choice for lowest-cost mode of transport.
- Containers need to be fully loaded to achieve optimum efficiency. Many small transport companies in developing countries, often with individual truck owners, prefer small trucks over container transport. Fuel subsidies makes trucking more competitive than barging for which no such subsidy scheme exists.

To calculate the costs per tonne for each mode of transport, surveys with transport companies have been carried out. Costs are expressed in USD/t or TEU/t for containers (see Table 5.7).

To gain a precise insight in total transportation costs between origin and destination, it may well be that cargo changes modes of transport. This is for instance applicable to container transport which requires loading and offloading in a port onto trucks before it can be delivered to the final destination. In some cases, the container is emptied in a warehouse from where individual cargoes are transported further. It is therefore important to gain insight into the complete corridor of transport rather than the individual legs.

Mandalay to Yangon Comparison	ROAD	RAIL	RIVER
Cost $/t (Min)	$50	$54	$32
Cost cents/t/km	7.1c	8.7c	3.5c
Distance (km)	705	617	917
Timing (days)	2	4	7
Capacity	▪ Cargo trucks/break bulk: 15-27 tonnes (12 wheelers) ▪ Oil tankers/Liquid bulk: 3 kinds: 2,800 gal; 5,200 gal; 7,000 gal	▪ 1,500 horsepower: 15 freight cars, each car taking max. 30 tonnes or 15 containers ▪ 2,500 horsepower: 30 freight cars, each car taking max. 30 tonnes or 30 containers	▪ Cargo Barges (200 x 50ft.) – Tonnage (DWT): 600t-Dry, 1000t-Wet (Max: 1000-1200) – Containers (20ft.): 1 "level": 42 containers; 2 "levels": 60-80 containers (Max) – Draft (when loaded): 1.4 m ▪ Oil Barges: – Gallons (US gl.): 280,000 (in dry), 350,000 (in wet) ▪ Land Craft Transporters – Tonnage (DWT): 600t-Dry, 1000t-Wet (Max: 1000-1200) – Vehicles: tractors and heavy machinery and equipment
Advantages / disadvantages	▪ Road is direct, fast and necessary per shipment ▪ Road has a wide network ▪ High cost, low volume per shipment	▪ Rail is larger volume per shipment ▪ Rail network is less direct ▪ Cost is high due to excessive handling	▪ Lowest cost per tonne by far ▪ River is by far the largest volume per shipment ▪ Has the least direct network

Table 5.7: Comparison of different modalities to transport cargo between Mandalay and Yangon along the Ayeyarwady River (for illustrative pruposes only) (by Royal HaskoningDHV is licensed under CC BY-NC-SA 4.0).

Since the improvement of roads in Myanmar, larger trucks were able to travel larger distances much faster. The time to deliver goods from Mandalay to Yangon currently requires 2 days by truck, whereas rail would take 4 days and by river transport 7 days.

The reliability of transport is often expressed as the variation in travel time. Congestion on roads can increase the road travel time considerably, sometime heavily influenced by weather conditions and poor road maintenance. Rail is often reliable as there is a fixed schedule, but delays as a result of train failure or track repairs can be substantial. River transport experiences delays during the dry season, where some shallow sections on the river cannot be used for several days.

Shippers factor this into their price as well, hence dry season transport is more expensive than wet season transport. Investments into river transport improvements are often dedicated to removing bottlenecks, to increase the reliability of this mode of transport.

Figure 5.18 presents the transportation time of goods from the origin to destination, in which all steps are defined in terms of time and costs (USD/t).

Step 4: Market Share and Capacity River Port

Based on the regional market forecast for the cargo and the distribution of cargoes between various modes of transport, a cargo volume forecast that can be attracted by the new river port was made (Figure 5.19). For each cargo, the costs, time and reliability were mapped. A relative share of cargo to each mode was made, based on the preferences expressed by cargo owners, through surveys. Especially liquid bulk cargo and other cargoes proved to be most attractive. Those producing high-value goods which are usually transported by container would prefer trucking, and hence the total share will be relatively low.

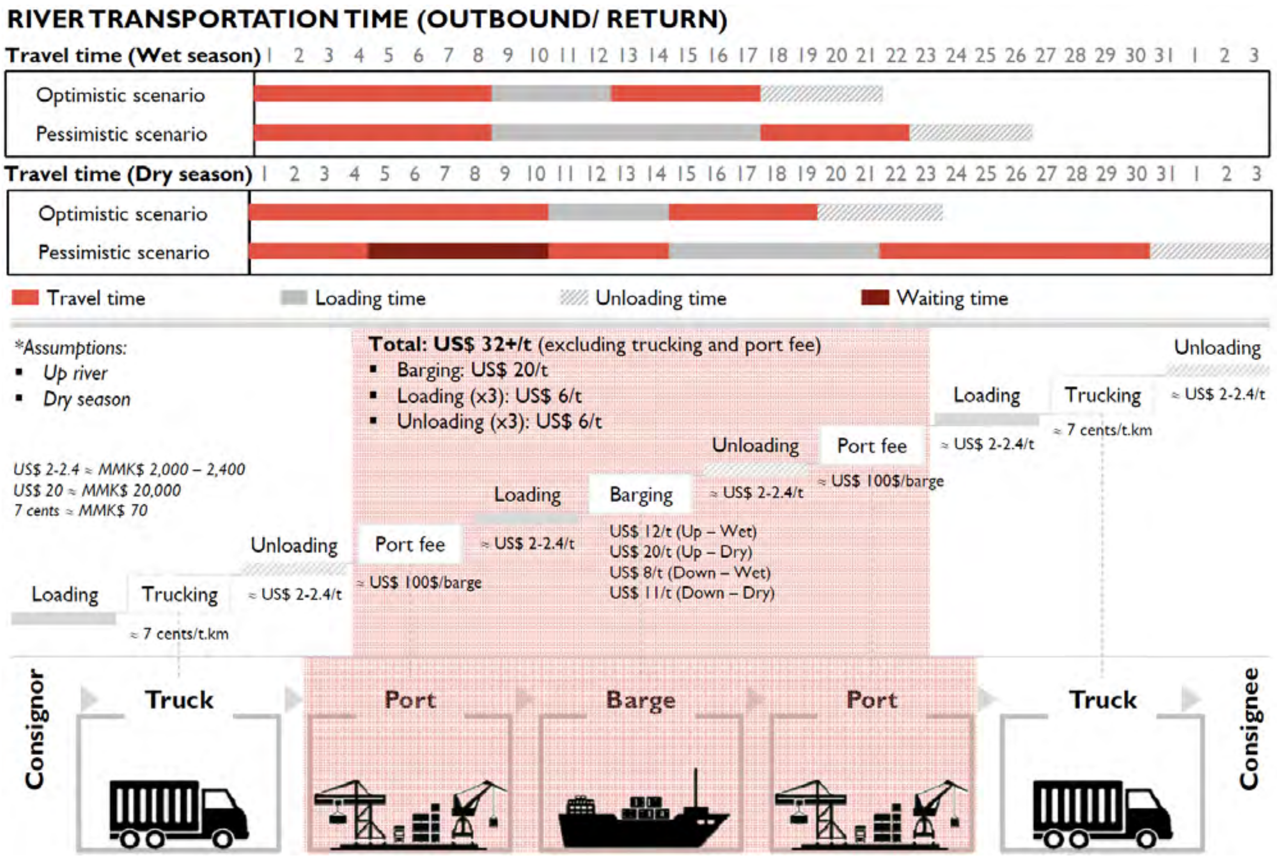


Figure 5.18: Transportation time from goods from the origin to destination (for illustrative pruposes only) (by Royal HaskoningDHV is licensed under CC BY-NC-SA 4.0).

This forecast was used to design the river port facilities with adequate capacity to handle these volumes. The designs are then used to make a CAPEX and OPEX estimate.

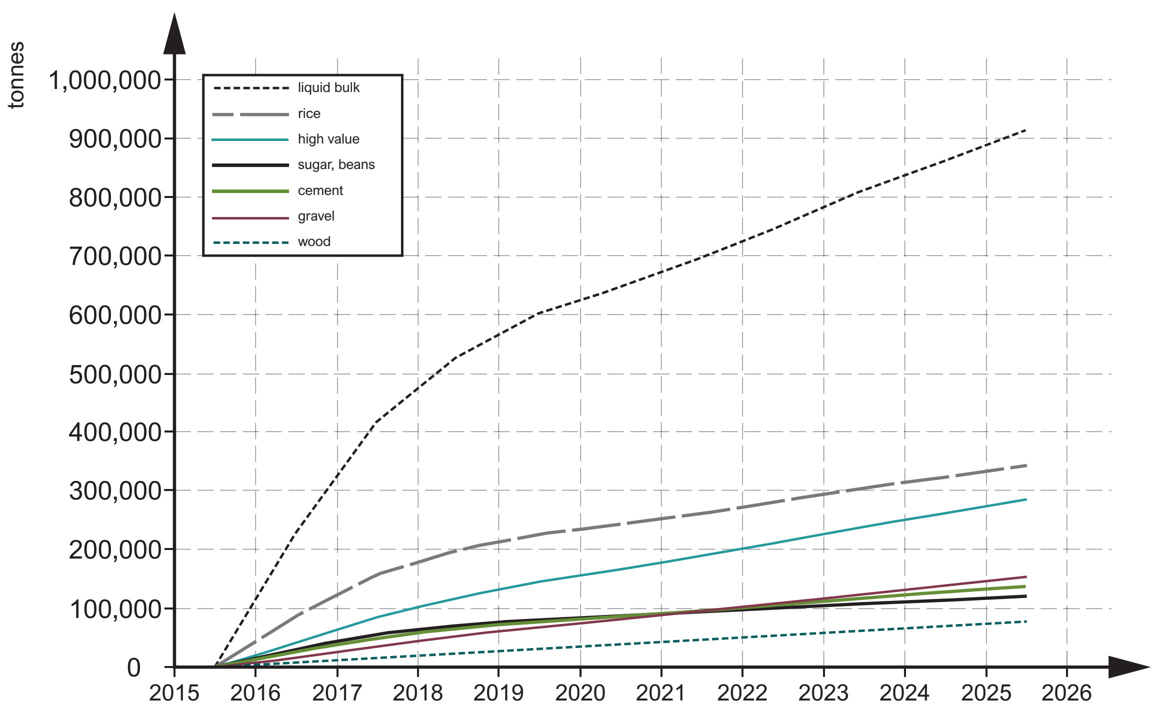


Figure 5.19: Transportation scenarios for different types of cargo (for illustrative pruposes only) (by Royal HaskoningDHV is licensed under CC BY-NC-SA 4.0).

Step 5: Tariff study and business case

As a final step, the cost advantage of using the river port over other modes of transport, in combination with the estimated running costs (also expressed in USD/t) of such a port, are used to determine the fee that can be charged to the shipping companies (Figure 5.20). A positive business-case is found once both shipping companies and river port operator have sufficient margins. Very high fees for using the river port can divert cargo from river transport to roads or rail. Very low fees will result in an unprofitable river port which will not be financially sustainable. It may therefore be concluded that before a successful (river) port project will be financed and constructed, a good insight into the transport economics, logistics and port capacity is required. In the below example, a potential port fee of 8 USD/t is calculated. This means that to remain competitive, a port fee of maximum 8 USD/t can be charged. The port fee should be sufficient to cover the costs of constructing and running the proposed river port to the required capacity.

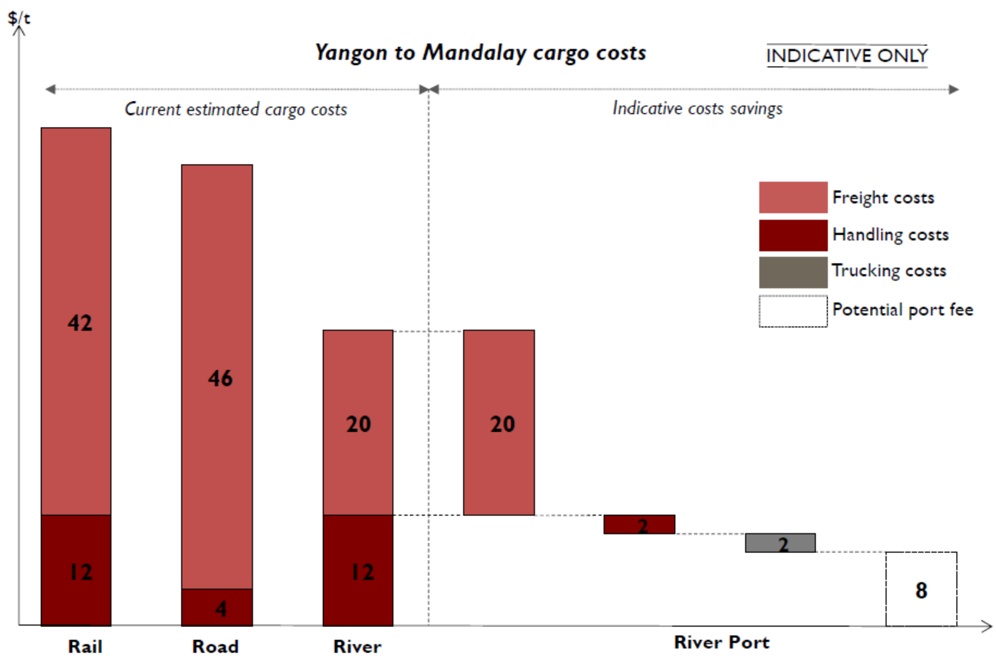


Figure 5.20: Cost comparison of alternatives and potential fee (for illustrative pruposes only) (by Royal HaskoningDHV is licensed under CC BY-NC-SA 4.0).

5.4 Concluding

Section 5.3 describes an example of a multi-modal corridor analysis. It is interesting to see how all elements in this book play a role there. To fully grasp the complexity of a corridor, you need to understand current and future demand, the current and future modality mix (including the vessel mix) and the status of the network of ports/terminals and waterways. To investigate multiple potential system configurations, simulation is crucial.

Epilogue

Reflection – theory vs practice

You have reached the end of the book 'Ports and Waterways – Navigating the changing world'. In this book we integrated the content of a number of separate lecture notes used in our teaching activities. This integration reflects our vision that ports and waterways should be viewed as parts of a coherent system that supports waterborne supply chains, and that their integral design and operation is essential. We argued that port and waterway networks are subject to drivers that trigger a constant need for change. That this argument is not just theoretical is demonstrated by a number of real-world developments that took place while we were writing this book:

- In 2018 the largest drought in decades, resulted in severely reduced water levels on the Waal, the Netherlands, and onward into Germany. This impacted inland shipping on the Rhine-Alpine corridor for nearly six months, causing shortages in fuels and building materials far into Rotterdam's hinterland.
- From the end of 2019 onward the global COVID-19 pandemic had a significant impact on global waterborne trade. In the first months of 2020 global transport volumes dropped sharply and idled ship capacity increased significantly. The sudden reduced demand for oil, combined with a continued supply, led to a subsequent shortage in oil storage capacity, which caused oil prices to become negative for a brief period of time in April 2020.
- After the initial shock of COVID-19, trade started to recover in the second half of 2020. An unprecedented shortage of containers caused a massive surge in container freight rates. This caused significant disruption in global supply chains, hampering the COVID-19 trade dip recovery.
- On August 4th 2020, 2,750 tonnes of ammonium nitrate exploded in the port of Beirut, leading to 218 deaths and thousands of injuries, leaving several hundred thousand people homeless, and causing billions of dollars in property damage. The damage to the country's main port instantly disrupted Lebanon's supply chains.
- On March 23rd 2021, container vessel Ever Given ran aground in the Suez Canal. The vessel blocked all trade for a period of six days, until salvage crews managed to free it on March 29th 2021. The incident illustrated how vulnerable global waterborne supply chains are to disruptions in the network.
- Starting January 1st 2021, the EU-UK Trade and Cooperation Agreement became active after years of negotiating following the 2016 Brexit referendum. In combination with the effects of COVID-19 the UK's trade volumes (import and export) dropped significantly in the first 6 months of 2021. Substantial additional paperwork impacted the flow of goods between the EU and the UK and resulted in emergence of alternative water transport routes. Stricter immigration rules caused significant shortages in lorry drivers which in turn gave rise to empty shelves in UK supermarkets in the summer of 2021.
- In July 2021 extreme precipitation (two months worth of rain fell in the course of just a few days), caused discharges on the Maas, the Netherlands, to achieve record levels associated with a return period of 50 – 100 years. Other countries that were similarly affected by the event were Belgium, Germany, France, Italy, Luxembourg, Austria, The United Kingdom and Switzerland. Next to severe flooding, with significant loss of life and material damages, also shipping was halted during this event. The fact that these extreme high discharge levels occurred during the summer made the situation particularly unique.
- On July 14th 2021, the EU adopted legislation to achieve climate neutrality in the EU by 2050. For the year 2030 an intermediate target of at least 55% net reduction in greenhouse gas emissions was defined. The adopted legislation implements the EU climate targets under the European Green Deal, and will have a significant impact on all economic sectors in the EU, including shipping.

The events listed above, while having been widely visible in the local and international media, represent only part of all the developments that are going on in the field of ports and waterways. Each of these developments requires port and waterway managers, shipping companies, regulating authorites, etc., to adjust the way they operate, both in the short term and in the long term. In many cases, infrastructure development and modification will be part of the mix of interventions that are being considered.

Navigating the changing world

As this book has shown, the design and operation of port and waterway systems is a complex challenge that requires the involvement of many disciplines. External triggers force actors to continuously review which measures they need to take to adapt to the changing world. Non-linear feedbacks that exist in and between these systems increase the demand for port and waterway professionals that are able to deal with this complexity and develop and compare alternative strategies for the design and operation of waterborne supply chains. This requires a thorough understanding of the key elements of port and waterway systems, and their complex interactions, in order to create a system in which transport capacity, efficiency, safety and sustainability meet pre-defined objectives in a well-balanced way. Not only will this require more complicated analyses, where new data sources and simulation techniques are utilised to their full potential, but it will also require a more adaptive mindset.

As the previous section has shown, triggers of change can occur unexpectedly and be extremely impactful. The record droughts and floods, as well as the apparent increase in heat waves and forest fires, might be early signs of the long predicted climate change impacts. If these signs are reinforced in coming years, as the recently published (August 7th, 2021) scientific basis for the 6th Assessment Report (AR6) (IPCC, 2021) suggests, a more drastic focus on emission reduction and a significant acceleration of the transition to renewable forms of energy are imminent. This transition will not only bring technical challenges, but it may also impact our current views on globalisation, with shifting trade flows as a potential consequence. In any case this development is likely to influence the field of ports and waterway engineering for decades to come.

While some of these prospects may seem intimidating and even scary, the need to adapt will also be challenging. Port and waterway engineers must work together with other disciplines to quickly understand new circumstances as they occur. New strategies and solutions must be devised, tested, selected and implemented under time pressure and in a Volatile, Uncertain, Complex and Ambiguous (VUCA) world. We hope that this book will inspire students to prepare themselves for the challenges ahead. Knowledge will be a key asset to navigate the changing world, as long it is combined with wisdom.

Prof. dr. ir. Mark van Koningsveld,
8th February 2023,
on behalf of TU Delft's Ports and Waterways team.

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List of Symbols

Symbol	Unit	Description
A	m^2	surface area
A	-	arrival process
A_c	m^2	wet cross-sectional area of the undisturbed channel
A_{cfs}	m^2	surface area of the CFS
A_{ch}	m^2	chamber floor area (horizontal); channel wet cross-sectional area
A_{ci}	m^2	imaginary wetted cross-sectional area
A_{gr}	m^2	gross storage area
A_{ladens}	m^2	total storage area for ladens
A_{lock}	m^2	cross-sectional area of a lock chamber
$A_{lock,s}$	m^2	cross-sectional area of a lock chamber at the stern of a ship in a lock
A_{oogs}	m^2	total storage area for oogs
$A_{reefers}$	m^2	total storage area for reefers
A_s	m^2	wetted cross-section of the midship section of a shop
A_{sl}	m^2	opening area of a sluice
A_{st}	m^2	cross-sectional area of the bulb at still water level
A_{ST}	m^2	gross area per stack
A_T	m^2	area of the immersed part of the transom stern at zero speed
A_{TEU}	m^2	gross ground slot area
A_0	m^2	cross-sectional area of the outflow opening of an orifice
B_c	m	width container
B_s	m	beam; width of a ship at the midships-section
B_v	m	width of the virtual space around a sailing ship
c	m/s	celerity of an individual wave in unrestricted water
c	-	call size
c	-	number of servers
c	-	coefficient
c_f	-	friction coefficient
$c_{f,deep}$	-	friction coefficient in deep water
$c_{f,Katsui}$	-	Katsui's friction coefficient for a flat plate in unrestricted water
$c_{f,shallow}$	-	friction coefficient in shallow water
$c_{f,0}$	-	frictional resistance according to the ITTC'57 curve
c_t	m/s	celerity of a transversal wave
c_0	m/s	initial celerity translation wave
c_1	m/s	celerity translation wave bounced back by a lock door
C	-	coefficient
C	t/yr; TEU/yr	capacity
C	t/yr; TEU/yr	cargo flow or annual throughput
C	s^{-1}	capacity, i.e. maximum possible traffic intensity
C_b	t/yr; TEU/yr	berth productivity; berth capacity
$C_{empties}$	TEU/yr	throughput of empties
C_f	-	friction coefficient in resistance relationship
C_k	TEU/yr	througput of containers category k over the storage area
C_{laden}	TEU/yr	throughput of ladens
C_n	currency	present value
C_{nr}	currency	real value
C_o	currency	invested capital
C_{oogs}	TEU/yr	throughput of oogs

C_p	-	pressure resistance coefficient
$C_{reefers}$	TEU/yr	throughput of reefers
C_{req}	TEU	total capacity required
C_{st}	$TEU/stack$	total capacity per stack
C_{WP}	-	waterplane area coefficient
C_B	-	block coefficient
C_M	-	midship section coefficient
C_P	-	prismatic coefficient
C_S	s^{-1}	lock capacity per time unit
C_T	t/s	lock capacity in tonnes
$C(n,p)$	-	Erlang's C formula
C_3	-	coefficient
d	-	empirical parameter
d_{yr}	$days/yr$	number of operational days per year
D	-	traffic density
D	-	queue discipline
D_{air}	m	air draught
$D_{air,90\%}$	m	air draught not exceeded by 90% of the unladen vessels
D_b	m	bowthruster diameter
D_0	m	effective propeller jet diameter
D_{crit}	-	critical traffic density when the traffic capacity equals the traffic intensity
D_{eq}	m	equivalent diameter
D_{loaded}	m	draught of a laden vessel
D_p	m	propeller diameter
D_s	m	draught(of non-moving ship)
$D_{s,bow}$	m	draught at the bow of a ship
$D_{unloaded}$	m	draught of an unladen vessel
D_{50}	m	average grain size diameter; characteristic diameter bottom protection
$D_{50\%}$	m	draught that is exceeded by 50% of all ships in a particular class
DWT	t	deadweight tonnage
em_{CO_2}	$kg/tonkm$	total emission rate of CO_2
Em_x	t	total emission of gas x during a trip
Em_{CO_2}	t	total emission of CO_2 during a trip
EF_x	t/kWh	efficiency factor for gas x
EF_{CO_2}	t/kWh	efficiency factor for CO_2
f	-	number of customers in the system
f_a	Hz	apparent wave frequency
f_{area}	-	ratio gross area over net area
f_{bulk}	-	bulking factor
f_p	-	peak factor
f_p	-	percentage of maximum installed engine power main propeller or bowthruster
fp_{day}	-	factor of peak week moves at a peak day
fp_{hour}	-	factor of peak day moves at a peak hour
fp_{week}	-	factor of peak year moves at a peak week
f_r	-	irregularity factor for vessel arival
f_{reef}	-	stack reefer factor
f_{TEU}	-	TEU-factor
$f(t)$	-	probability density function
F	N	force
F	m	freeboard
F_{fr}	N	force on a ship in a lock due to the friction
F_h	N	hydrostatic force
F_{in}	-	flux of customers entering the system
F_{jet}	N	force on a ship in a lock due to the filling jet against the bow

F_{out}	-	flux of customers leaving the system
F_p	N	pressure force on a rudder
F_{ship}	N	total force on a ship in a lock
F_{tw}	N	force on a ship in a lock due to translatory waves
F_B	N	force on a ship in a lock due to the Bernoulli effect
F_D	N	transverse flow force due to sailing of the ship with a drift angle
F_H	N	resulting transverse force due to sailing of the ship with a drift angle
F_L	N	longitudinal force on a rudder
F_R	N	rudder force
F_T	N	transverse force on rudder
F_x	N	longitudinal force on a ship in a lock
Fr_h	-	Froude number related to ship speed and water depth
Fr_{lim}	-	Froude number related to limit ship speed and water depth
Fr_L	-	Froude number related to ship speed and ship length
F_ρ	N	force on a ship in a lock due to a density gradient
F_1, F_2, F_3	N	force on a ship passing a side canal
g	m/s^2	acceleration of gravity
gpf	-	gate peak factor
GT	t	gross tonnage (volume in units of 2.83 m^3); not related to cargo weight, but to the volume of the holds of a ship
$h(t)$	s	time step in queueing theory
h	m	water depth
h_b	m	water depth at the bow of a ship in a lock
h_c	m	average height of cargo
h_p	m	distance between propeller axis and channel bed
h_q	m	water depth at a quay
h_{ref}	m	average water depth in a river at the discharge at which the groynes submerge
h_s	m	water depth at the stern of a ship in a lock
h_B	m	position of the centre of the bulb cross-section at the waterline above the keel line
$\overline{h}$	m	schematized water depth ($= A_c/W_s$)
h_0	m	initial water depth; water depth of the undisturbed canal
H	m	head difference
H	m	sheerline depth
H_c	m	height container
H_i	m	wave height of interference cusps
$H_{n,st}$	TEU	nominal stacking height
H_s	m	significant wave height
H_t	m	wave height of transversal wave
H_B	m	head room
i	-	gradient
i	-	inflation rate
i_E	-	angle of the waterline at the bow with respect to the central plane
i_{max}	-	maximum water level gradient
I	s^{-1}	traffic intensity
I/C	-	traffic load
k	-	blockage coefficient ($= 1/n = A_s/A_c$)
k	-	wave number
k	-	number of locking cycles
k	m	keel clearance during sailing ($k < UKC$)
k_c	m	keel clearance in a lock
k	-	parameter in Poisson distribution
k_1	-	coefficient in the form factor of the hull
k_2	-	coefficient in the appendage form factor
K	-	number of places in the system

K_t	currency	annual costs in year t
l	m	path length
l_0	m	distance between two vessels along a quay
l_s	m	distance behind or in front of a vessel to the end of quay
L	m	length of a water way section
L	m	distance between outflow opening bowthruster to quay
L_c	m	length container
L_d	m	deceleration area near a lock
L_d	m	wave length divergent waves
L_e	m	entrance length of a lock
L_{lock}	m	lock length
L_m	m	marshalling area of a lock
L_q	m	quay length
L_q	-	long term average number of customers waiting in the queue
L_s	m	ship length; main vessel length
L_s	-	long term average number of customers present in the system
L_{st}	m	stopping distance
L_t	m	wave length transversal waves
$L_{t,m}$	m	transport distance in meters
$L_{t,km}$	m	transport distance in kilometers
L_v	m	length of the virtual space around a sailing ship
L_w	m	length of waiting area in a lock arrangement
L_{wi}	m	wave length of interference cusps
LBP	m	length between perpendiculars
L_{WL}	m	water line length
L_{OA}	m	length over all
L_R	m	length parameter
LF	-	load factor, i.e. ratio of operational power to maximum power a device can have
m	-	bank slope
m	-	discharge coefficient
m	m	safety margin
m_b	-	occupancy rate of berth
m_c	-	occupancy rate
m_{cap}	-	highest occuring dead-weigth capacity class
m_1	-	empirical parameter
m_2	-	empirical parameter
M	t	mass of the ship in tonnes
M	$kg/(ms^3)$	erosion coefficient
M_{max}	-	peak number of moves per hour
M_y	-	number of moves per year
M_D	Nm	moment due to drifting
M_H	Nm	moment due to total transverse forces
M_R	Nm	turning moment
M_T	Nm	moment due to transverse force
n	-	number of berths
n	-	number of ships
n	-	blockage ratio (=Ac/As)
n	-	number of years
n	-	number of n-th wave crest from the bow
n_d	-	number of operational hours per year; berth availability
n_h	-	number of operational hours per day
n_{max}	-	average number of ships per locking operation in a large number of operations with a full loc
n_d	-	number of vessels to be locked in a downstream phase
n_u	-	number of vessels to be locked in an upstream phase

n_w	-	number of operational vessels
N	-	number of (un)loading units operating on a ship of average size
N	-	number of individuals in the calling population
N	-	number of arrivals in a time interval of a fixed length t
N_c	-	number of container movements per year per type of stack in TEU's
N_{fgs}	-	number of FEU ground slot for containers
$N_{fgs,st}$	$fgs/stack$	total FEU ground slots per stack
N_{sk}	-	number of TEU of category k to be stacked
N_{st}	-	number of stacks required
N_{tgs}	-	number of TEU ground slot for containers
$N_{tgs,st}$	$tgs/stack$	total TEU ground slots per stack
N_{tot}	-	sum of N20 and N40
N_{20}	-	number of TEU's
N_{40}	-	number of FEU's
NRT	t	net register tonnage (expressed in units of 2.83 m3); not related to cargo weight, but to the v
p	t/hr	pump capacity
p	TEU	effective capacity of (un)loading equipment
pdf	-	probability density funtion
pf_{day}	-	busiest day in the peak week
pf_{hour}	-	busiest hour in the peak day
pf_{week}	-	busiest week in the peak year
P	t/hr; TEU/hr	(un)loading capacity per unit loading equipment
P_b	kW	brake horse power BHP; engine power used by a ship
P_d	kW	delivered horse power DHP to the propeller
P_e	kW	effective horse power EHP
P_{hotel}	kW	power required for systems on board
$P_{\text{propulsion}}$	kW	(engine) power at propeller axis of main propeller
P_{total}	kW	total required (engine) power
P_s	kW	(engine) power at propeller axis
P_s	-	percentage of the vessel class in a traffic mix
$P_{n(t)}$	-	probability that at time t there are n number of customers in the system
$P_{n(t+h)}$	-	probability that at time t plus a time step h there are more customers in the system
$Pr\{S\}$	-	probability distribution of services
$Pr\{A\}$	-	probability distribution of arrivals
Q	m^3/s	discharge
Q_f	m^3/s	filling discharge
Q_{max}	m^3/s	maximum discharge
Q_0	m^3/s	filling discharge at t=0
Q_1	m^3/s	filling discharge at t=1
r	-	rate of return or discount rate
r	m	wave response
r	m	radial distance to the axis of the propeller jet
r'	-	discount rate corrected for inflation
r_{st}	-	ratio of average stacking height and nominal stacking height (0.6 to 0.9)
R	-	correlation coefficient
$R2$	-	coefficient of determination
R_{app}	N	appendage resistance
R_{bend}	m	bend radius
R_f	N	frictional resistance
R_p	N	pressure resistance
R_{res}	N	residual resistance
R_w	N	wave resistance
R_T	N	total resistance
R_e	-	Reynolds number

RC	currency	running costs of a berth
s	m	distance
s	-	vessel class
s	t	time in queueing theory
s_{max}	m	maximum sinkage (fore or aft) due to squat and trim
S	-	service process
S	m^2	submerged wetted surface of a ship
S	m	safety margin at bridges
S_{app}	m^2	wetted area appendages
S_b	N	momentum flux at the bow of the ship due to the jet filling the lock and hitting the ship's bow
S_q	-	probability that an arriving ship has to wait before being served
S_B	m^2	area of the flat bottom of a ship
$S(t)$	-	quantity of containers still on terminal t after the initial call
$S(0)$	-	quantity of containers of a call at $t = 0$
S_l	m	loop distance
t	s	time
t	t	cargo in tonnes
t	-	thrust deduction factor
t_d	day	dwell time
$t_{d,g}$	day	design time for gate operations
t_{dmax}	day	maximum dwell time (e.g. time within which 98% of containers have left the terminal)
t_{eff}	-	effective number of operational hours per year
$t_{g,entry}$	s	number of entry inspection minutes per hour
$t_{g,exit}$	s	number of exit inspection minutes per hour
t_i	s	entry following time
t_{is}	s	entry following time for (dead-weigth capacity) class s
t_l	s	loop time
t_{lost}	s	lost time of an individual vessel
t_p	s	passage time of an individual ship
t_s	s	locking time
t_u	s	following leaving time; exit following time
t_{us}	s	exit following time for (dead-weigth capacity) class s
t_w	s	waiting time
t_{wr}	s	remaining waiting time prior to entering a lock
T	s	filling time (total)
T	m	tidal restriction or tidal window
T	t	interarrival time
$\overline{T}$	t	average interarrival time
T_B	t	total bollard pull
T_c	s	cycle time lock
T_{ch}	s	time required to fill or empty a lock chamber
T_{close}	s	time required to close lock doors
T_d	s	locking duration
$\overline{T}_{dw}$	t	average dead-weight carying capacity per vessel
T_p	s	peak wave period
T_{op}	s	operating time lock
T_{open}	s	time required to open lock doors
T_s	t	average carrying capacity per ship in tonnes
$T_{waterlevel}$	s	equalizing the water level during a lock operation
T_{wi}	s	wave period of interference cusps
T_1	s	total opening time sluice
T_2	s	additional filling time after opening sluice
u	m/s	flow velocity

u_b	m/s	velocity near the bed
u_{max}	m/s	maximum flow velocity in the stern wave
U	m/s	water velocity; current velocity
U_c	m/s	current velocity in the undisturbed canal
U_{cross}	m/s	velocity of cross current
U_{lim}	m/s	limit return current velocity
U_{local}	m/s	local velocity
U_r	m/s	return current w.r.t banks
$U_{r,b}$	m/s	return current velocity underneath a sailing ship
U_r'	m/s	relative maximum return current (compared to the undisturbed canal)
$U_{r,lim}$	m/s	limit return current w.r.t banks
U_w	m/s	wind speed
$U_{r,1}$	m/s	return current caused by ship to be overtaken
$U_{r,2}$	m/s	return current caused by overtaking ship
$U_{r,3}$	m/s	return current caused by ship to be overtaken and overtaking ship
UF	-	utility factor, i.e. indicates to what extent a device is used in a particular situation
UKC	m	Under Keel Clearance
V	m^3	contents of 1 TEU container
V	m/s	flow velocity
V_{axis}	m/s	velocity in the axis of the propeller jet
$V_{b,max}$	m/s	maximum flow velocity at the bed due to a propeller jet
V_{crit}	m/s	ship speed when the traffic intensity equals the traffic capacity
V_i	m/s	speed of ship i
V_{lim}	m/s	limit speed of a ship
$V_{lim,1}$	m/s	limit speed of the ship to be overtaken
$V_{lim,2}$	m/s	limit speed of the overtaking ship
V_{max}	m/s	maximum velocity in propeller jet due to two propellers
V_0	m/s	ship speed at very low traffic density
V_0	m/s	efflux velocity
V_p	m/s	speed pressure point
V_s	m/s	sailing speed
$V_{s,1}$	m/s	sailing speed of the ship to be overtaken
$V_{s,2}$	m/s	sailing speed of the overtaking ship
V_s'	m/s	relative sailing speed of the ship (compared to the undisturbed canal)
V_{single}	m/s	flow velocity in the jet of a single propeller
$V_{x,r}$	m/s	flow velocity in the propeller jet at location x,r
V_A	m/s	advance speed of a ship's propeller
w	-	wake fraction
W	m	navigable width on a river
W_a	m	width addition to the swept path
$\sum W_a$	m	sum of additional widths
W_b	m	bank clearance
W_{bm}	m	swepth path
W_d	m	width at the canal bottom
W_f	kg	amount of fuel needed to produce the amount of power for a trip
W_{kc}	m	additional width access channel related to underkeel clearance
W_l	m	width of a lock
W_p	m	passing distance
W_q	t	long term average waiting time in the queue
W_s	t	long term average time present in the system
W_s	m	width of the channel at water surface level
W_{st}	TEU	stacking width
W_t	m	width of cross-section of inland waterway at the draugth of a loaded vessel
$\overline{W}$	m	schematised channel width ($= A_c/h_0$)

$\overline{W}$	m	navigable width in a river with navigable depth h_0
x	m	distance from the bow; distance from the propeller
x_b	m	distance of the ship's bow from the lock gate
$x_{b,min}$	m	minimum allowable distance of the ship's bow from the lock gate
x_n	m	position of the n-th wave crest
x_t	m	distance behind the ship
x_0	m	length of the core zone in a propeller jet
y	m	distance from the axis of the canal (eccentricity)
y_p	m	horizontal distance to the axis of the propeller jet
y_s	m	distance to the side of the ship
z	m	vertical distance compared to undisturbed water level (up is positive)
z	m	head
z	m	water level depression
z_b	m	bed level with respect to a fixed level
z_{lim}	m	maximum water level depression
z_{max}	m	maximum height of a translatory wave; height stern wave
z_0	m	initial height of a translatory wave
z_1	m	water level depression caused by ship to be overtaken
z_1	m	heigth translation wave bounced back by lock door
z_2	m	water level depression caused by overtaking ship
z_3	m	water level depression caused by ship to be overtaken and overtaking ship
α	$^\circ$	bend angle
α	$^\circ$	slope angle
α	-	coefficient
α_i	-	coefficient to determine wave height interference cusps (dependent on ship type)
α_{schijf}	-	correction coefficient Schijf
β	$^\circ$	drift angle
β_{eq}	$^\circ$	equilibrium drift angle
γ	$^\circ$	angle
γ_t	-	coefficient to determine wave height transversal waves
δ_r	$^\circ$	rudder angle
ϵ_d	kg/kWh	factor
Δ	t	ship displacement in tonnes (mass of displaced water)
Δ	-	relative density of stone protection ($= (\rho_s - \rho_w)/\rho_w$)
Δh	m	water level difference
Δt	t	trip duration
Δb	m	extra width for cross wind in cross-sectiondesign of inland waterways
ΔB	m	extra width in channel bends
η_g	-	gearing efficiency
η_h	-	hull efficiency
η_o	-	open water efficiency of the propeller
η_r	-	relative rotative efficiency of the propeller
η_t	-	transmission efficiency
η_z	-	head water in front of the bow of a vessel
η_T	-	efficiency coefficient in power-resistance relationship
θ	$^\circ$	angle interference peaks
λ	m	wave length
λ	t^{-1}	average arrival rate (per time unit) per berth
λ	-	empirical parameter
μ	t^{-1}	average service rate (per time unit) per berth
μ	-	coefficient
ν	m^2/s	kinematic viscosity
ρ	-	ratio of arrival time l and service rate m; r = l/m
ρ	kg/m^3	density

ρ_s	kg/m^3	density of sediment/stones
ρ_w	kg/m^3	density of water
τ_b	N/m^2	actual bed shear stress
τ_{cr}	N/m^2	critical shear styress for erosion
ϕ	$^\circ$	angle of propagation of interference peaks
∇	m^3	water displacement

List of Acronyms

AEIS Automatic Equipment Identification System. 134, 190
AGV Automated Guided Vehicle. 130, 131, 133, 143, 156
AIS Automatic Identification System. 270, 357, 424, 453–457
ALD Agreed Low Discharge. 423, 425
ALW Agreed Low Waterlevel. 185, 241, 423
APP Adaptive Port Planning. 51
ARA-area Amsterdam-Rotterdam-Antwerp area. 215
ARMG Automated Rail-Mounted Gantry. 156
ASC Automated Stacking Crane. 133
ATL Automatic Twistlock. 143

BCR Benefit Cost Ratio. 43
BD Basic Design. 68
BHP Brake Horse Power. 438, 446, 447
BPR Binnenvaart Politie Reglement. 237
BSC Barge Service Centre. 136
BwN Building with Nature. 45, 61

CAPEX CAPital EXpenditures. 41, 43, 105, 156, 202, 398, 404, 408, 410, 414, 461
CBA Cost-Benefit Analysis. 41, 44
CCNR Central Commission for the Navigation of the Rhine. 203, 241, 355
CD Chart Datum. 78
CEMT European Conference of Ministers of Transport. 202, 204, 205, 241, 265, 267, 291, 296
CEU Car Equivalent Unit. 74
CEVNI European Code for Navigation on Inland Waterways. 350, 351, 353
CFD Computational Fluid Dynamics. 333, 346, 427, 439
CFS Container Freight Station. 138, 154, 155
CNG Compressed Natural Gas. 74
CO Construct Only. 69
COLREG International Regulations for Preventing Collisions at Sea. 353
CSI Container Security Initiative. 159

D&B Design and Build. 69
D&C Design and Construct. 44
DBFM Design, Build, Finance, Maintain. 44
DBFMO Design, Build, Finance, Maintain and Operate. 44
DBMO Design, Build, Maintain, Operate. 44
DCM Design, Construct, Maintain. 44
DHP Delivered Horse Power. 438, 446
DMA Dynamic Mooring Analysis. 260, 432, 434, 435
DME Dimethyl Ether. 26
DRIP Dynamic Route Information Panel. 351, 352
DWT Dead Weight Tonnage. 22, 74, 76, 162, 167, 170

ECT Europe Container Terminals. 15, 130, 133, 136, 145
EHP Effective Horse Power. 438, 445, 446
EIA Environmental Impact Assessment. 36, 48, 49, 61, 69
EPC Engineering, Procurement, Construction. 69
ESIA Environmental and Social Impact Analysis. 45, 77
EU European Union. 45, 202

EWMB Emergency Wreck Marking Buoy. 350
EwN Engineering with Nature. 45

FAL Convention on Facilitation of International Maritime Traffic. 27
FCFS First Come First Serve. 380
FEED Front End Engineering Design. 68, 69
FEU Forty Feet Equivalent Units. 121, 125
FIFO First In First Out. 380
FIS Fairways Information Services. 196, 245, 349, 355, 397
FLT Forklift Truck. 129
FMCG Fast Moving Consumer Goods. 71
FoR Frame of Reference. 37–39, 362, 363, 452
FSA Formal Safety Analysis. 269
FSRU Floating LNG Storage and Re-gasification Unit. 167
FTS FastTime Simulators. 268

GDP Gross Domestic Product. 25, 71, 72, 126
GHG Greenhouse Gas. 26, 438
GPS Global Positioning System. 453
GRT Gross Registered Tonnage. 74
GT Gross Tonnage. 74

HAZOP Hazard and Operability. 168
HSC Hydrogen Supply Chain. 414

IALA International Association of Marine Aids to Navigation and Lighthouse Authorities. 349, 350, 352
ICT Information and Communication Technologies. 214
IMO International Maritime Organization. 26, 27, 29, 45, 48, 74, 159, 269, 349, 353, 355, 367, 437, 452, 453
IPCC Intergovernmental Panel on Climate Change. 26, 31, 32, 81
IRR Internal Rate of Return. 43
ISO International Standards Organisation. 121, 122
ISPS International Ship and Port Facility Security. 159
IVS Informatie- en Volgsysteem voor de Scheepvaart. 357
IWT Inland Water Transport. 26, 45, 57, 65, 68, 101, 102, 106, 112, 124, 134, 136, 138, 145, 151, 153, 166, 179, 180, 184–187, 189, 200, 204, 206, 207, 210, 218, 367, 395, 397, 401, 418, 423–425, 428, 437, 438, 447, 451–453, 455, 457

KNMI Royal Dutch Meteorological Institute. 32

LAT Lowest Astronomical Tide. 78
LCFS Last Come First Serve. 380
LCL Less than Container Load. 154, 401
LIFO Last In First Out. 380
LNG Liquified Natural Gas. 12, 26, 51, 71, 73, 74, 102, 161, 166–168, 370
LOHC Liquid Organic Hydrogen Carrier. 414
LPG Liquified Petroleum Gas. 26, 73, 74, 102, 161, 167, 168, 414, 416
LTD Longitudinal Training Dam. 248

MBS Maritime Buoyage System. 349
MCH Methylcyclohexane. 414–416
MHC Mobile Harbour Crane. 402–404, 409
MPE Main Propulsion Engine. 445
MRP Maximum Rated Power. 447
MSL Mean Sea Level. 78
MTS Multi Trailer System. 130, 131, 135, 143, 154
MZ Marine Zone. 168

NAP Normal Amsterdam Level. 78
NCF Net Cash Flow. 42
NII Non-Intrusive Inspections. 159
NIZ Non-Ignition Zone. 168
NPV Net Present Value. 42, 43, 364, 376, 398, 410–412

OBC Overhead Bridge Crane. 133
OBO Ore-Bulk-Oil. 175
OOG Out Of Gauge. 112, 122, 139, 143, 149, 150, 401
OPEX OPerational EXpenditures. 41, 43, 87, 105, 398, 404, 408–410, 414, 461

PAX Number of Passengers. 74
pdf probability distribution function. 378
PPE Personal Protective Equipment. 168
PPP Public-Private Partnership. 44
PQ Priority Queueing. 380
PTI Power-Take-In. 445
PTO Power-Take-Off. 445
PV Present Value. 42–44, 202

QRA Quantitative Risk Assessment. 168
QSC Quantitative State Concept. 38, 39, 363, 364, 438, 452

RAO Response Amplitude Operator. 433
RCP Representative Concentration Pathway. 31
RIS River Information Services. 214, 354
RMG Rail Mounted Gantry. 132, 133, 146, 158, 402, 404, 406
RMQC Rail Mounted Quay Crane. 403, 404
ROV Real Options Value. 43
RPR Rijnvaart Politie Reglement. 237
RS Reach Stacker. 129, 146, 402
RSC Rail Service Centre. 135, 136, 154
RTG Rubber Tyred Gantry. 131, 146, 158, 402, 406
RTS Real Time Simulator. 268

SC Straddle Carrier. 129, 143, 146, 402, 404, 406
SCBA Societal Cost Benefit Analysis. 36, 43, 44, 49
ShC Shuttle Carrier. 402
SIA Social Impact Analysis. 36
SIRO Service In Random Order. 380
SOG Speed Over Ground. 417, 420
SOLAS International Convention for the Safety of Life at Sea. 159, 218
SPM Single Point Mooring. 104
SPTF Shortest Processing Time First. 380
SSZ Safety and Security Zone. 168
STS Ship-To-Shore. 82, 109, 111, 127, 128, 136, 138–140, 143, 156, 401–404, 408, 409
STW Speed Through Water. 417, 420

TEN Trans-European Network. 202
TEN-T Trans-European Transport Network. 202
TEU Twenty Feet Equivalent Units. 21, 39, 71, 74, 107–109, 115, 117, 121, 124, 125, 139, 145, 154, 156, 364, 401, 408, 419, 420, 432
TGS Twenty-feet Ground Slots. 146
TOS Terminal Operating System. 158, 159
TSS Traffic Separation Schemes. 353
TT Tractor-Trailer. 143, 402

TVM Time Value of Money. 42, 53

UKC Under Keel Clearance. 142, 224, 227, 267, 301, 324, 327, 429
ULCC Ultra Large Crude Carrier. 75, 162
ULCV Ultra Large Container Vessel. 127

VHF Very High Frequency. 246, 357
VLCC Very Large Crude Carrier. 30, 60, 75, 164, 198
VLCV Very Large Container Vessel. 127
VTS Vessel Traffic Service. 19, 196, 204, 245, 246, 349, 355, 356, 358, 453
VUCA Volatile, Uncertain, Complex and Ambiguous. 50, 464

WHO World Health Organisation. 135
WwN Working with Nature. 45

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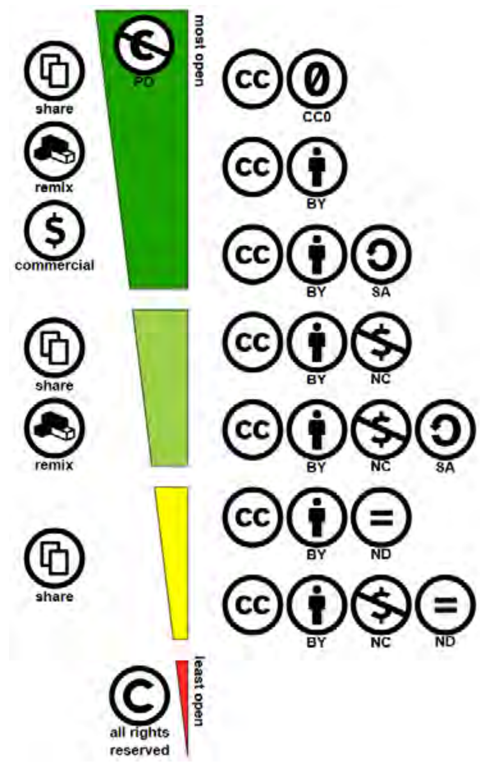

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Ports and Waterways - Navigating the changing world

Mark van Koningsveld, Henk Verheij, Poonam Taneja & Huib de Vriend

Synopsis

Before you lies the book 'Ports and Waterways -- Navigating the changing world', written by the Ports and Waterways team, part of the Civil Engineering and Geosciences faculty at Delft University of Technology. It integrates the content of a number of separate lecture notes we used in our teaching activities and updates this information where relevant. The integration reflects our vision that ports and waterways should be viewed as parts of a coherent system that supports waterborne supply chains, and that their integral design and operation is essential.

Groupname

TU Delft | Faculty of Civil Engineering and Geosciences

Biography:

Mark van Koningsveld *is professor Ports and Waterways at TU Delft, Faculty of Civil Engineering and Geosciences. He is furthermore affiliated with Royal Van Oord as Manager Innovation in the Engineering and Estimating Department. He specialises in science based decision making and has strong affinity with data science and sustainability.*

Henk Verheij *has 15 years of experience as senior lecturer Ports and Waterways at TU Delft, Faculty of Civil Engineering and Geosciences. He specialises in the interaction between vessels and vessel-induced water motions and their impact on hydraulic structures. He gained his expertise in the field of Inland Waterways during his more than 35 years affiliation as senior researcher with Deltares.*

Poonam Taneja *has been a lecturer Ports and Waterways at TU Delft, Faculty of Civil Engineering and Geosciences for several years. She furthermore teaches at IHE Delft, Institute for Water Education and the foundation for post academic education PAO. She holds a PhD in flexible port planning and adaptive design.*

Huib de Vriend *is emeritus professor River Engineering at Delft University of Technology. He developed an extensive trackrecord in academic research and innovation, also as scientific director of Delft Hydraulics and Deltares. In his role as director of the EcoShape foundation, he worked at the forefront of the Building with Nature innovation program, promoting a sustainable approach to hydraulic infrastructure development.*

TU Delft

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