Part II - Ch 2 Port planning

Lansen, A.J.; Quist, P.; Taneja, P.; van Koningsveld, M.; de Vriend, H.J.

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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.

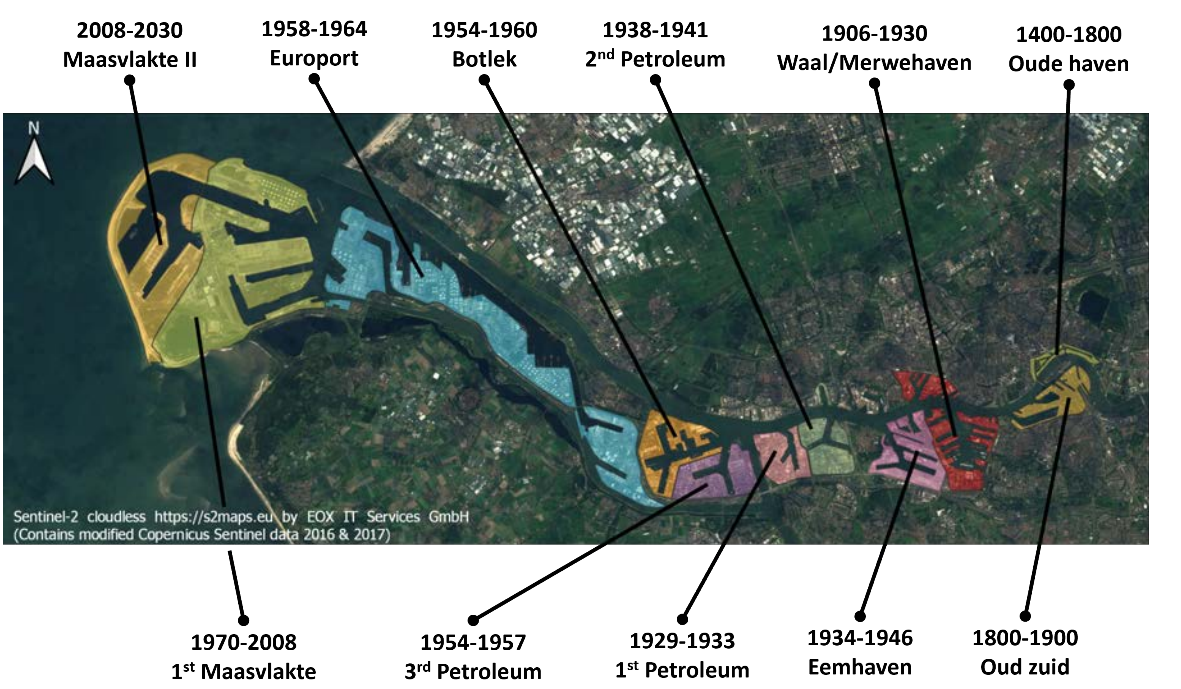

Figure 2.1: Development of the Port of Rotterdam over time (background: Sentinel-2 cloudless by EOX IT Services GmbH is licensed under CC BY 4.0, image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

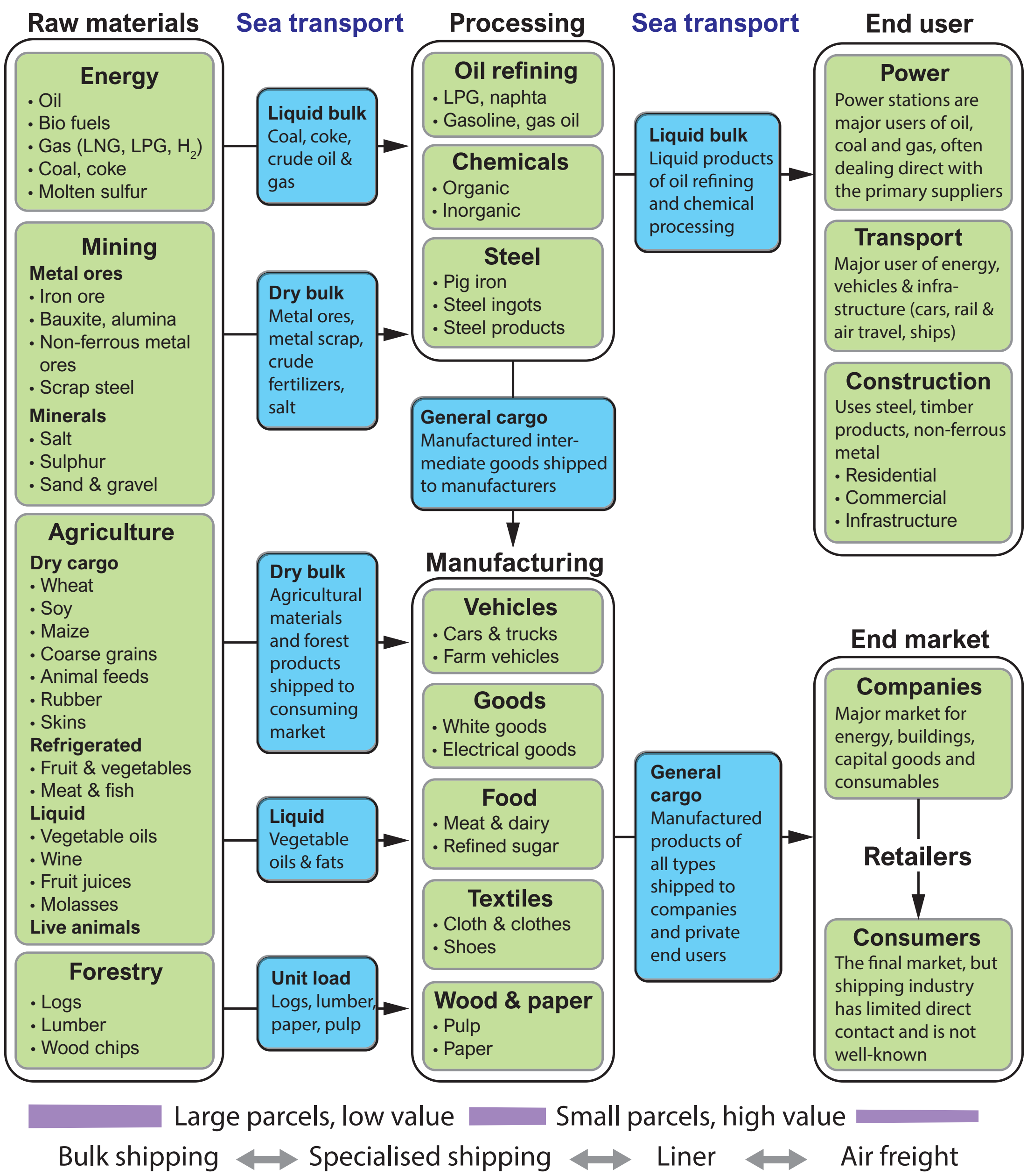

Figure 2.2: Transport requirements in the international transport system (modified from Stopford, 2008, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

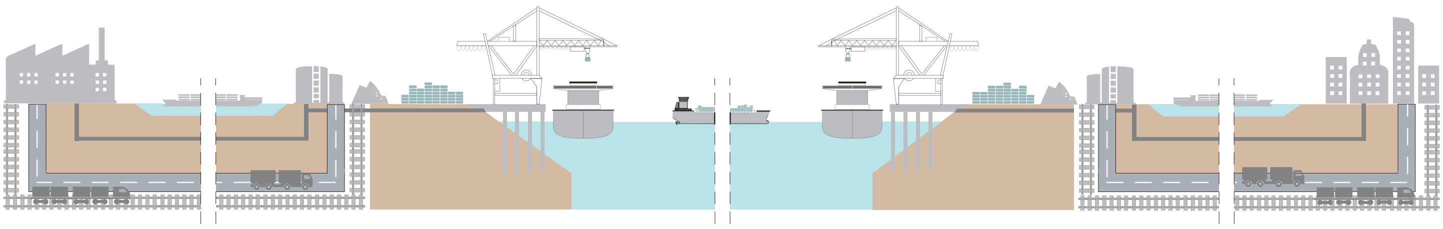

Figure 2.3: Overview of a supply chain, from source to end costumer (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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, 3^{rd} 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.

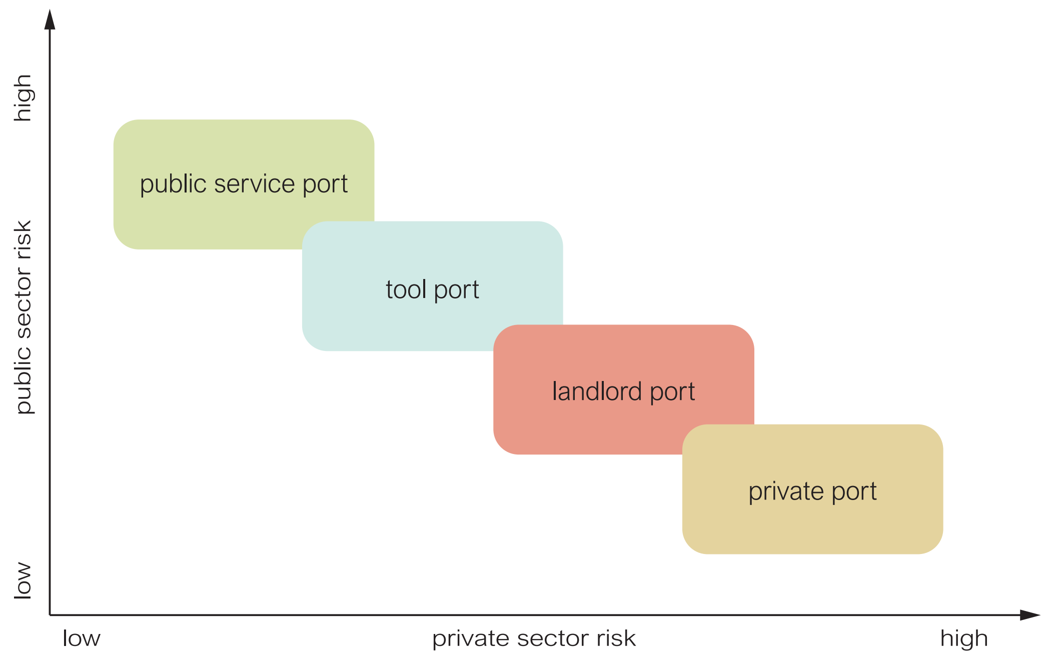

Figure 2.4: Port models distinguished by alternative combinations of risk-sharing between public and private sectors (reworked from Herrera Dappe and Suárez-Alemán, 2016, which is licenced under CC BY 3.0 IGO, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

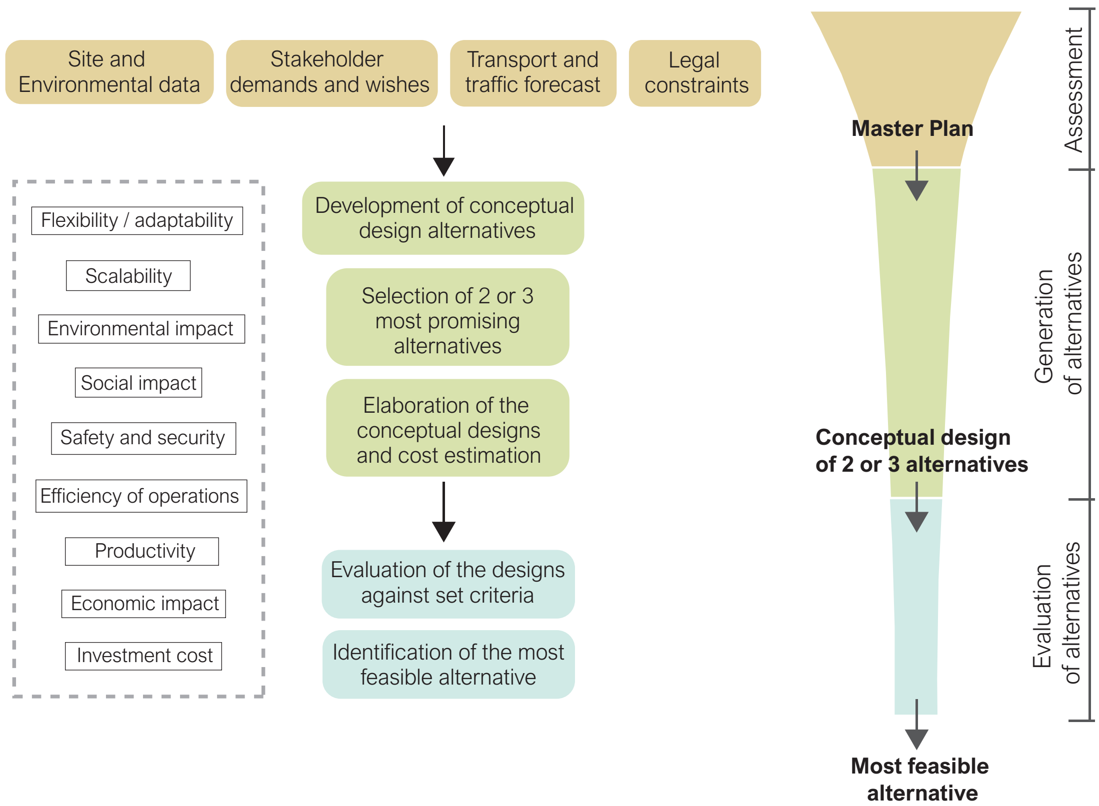

Figure 2.6: Flow chart of a port feasibility study (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

- 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).

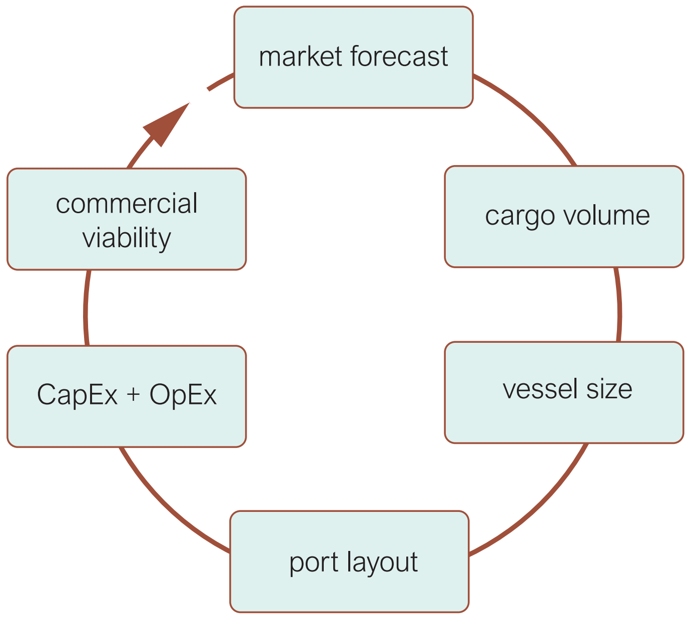

Figure 2.7: Iterative process in port development (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

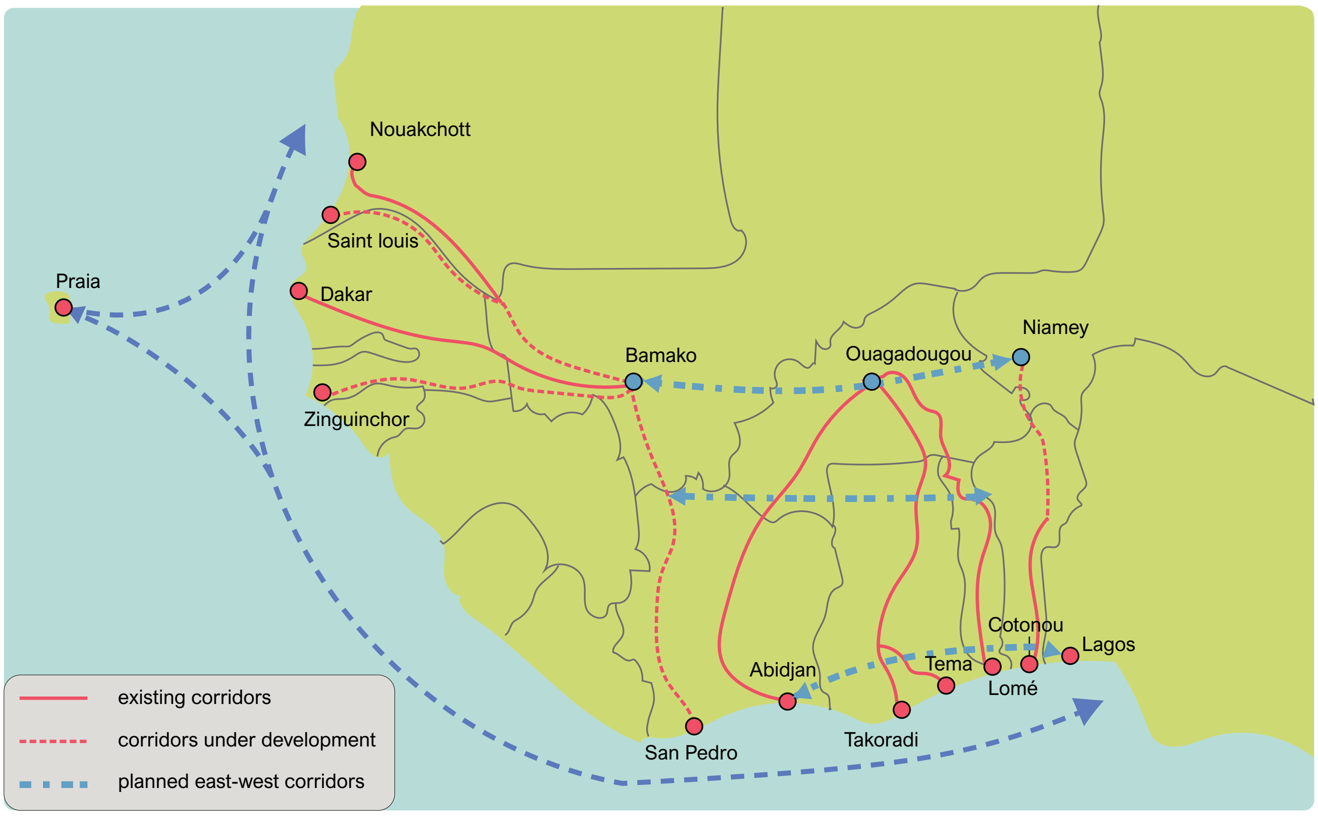

Figure 2.8: West African ports and corridors (source: Royal Haskoning DHV, image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

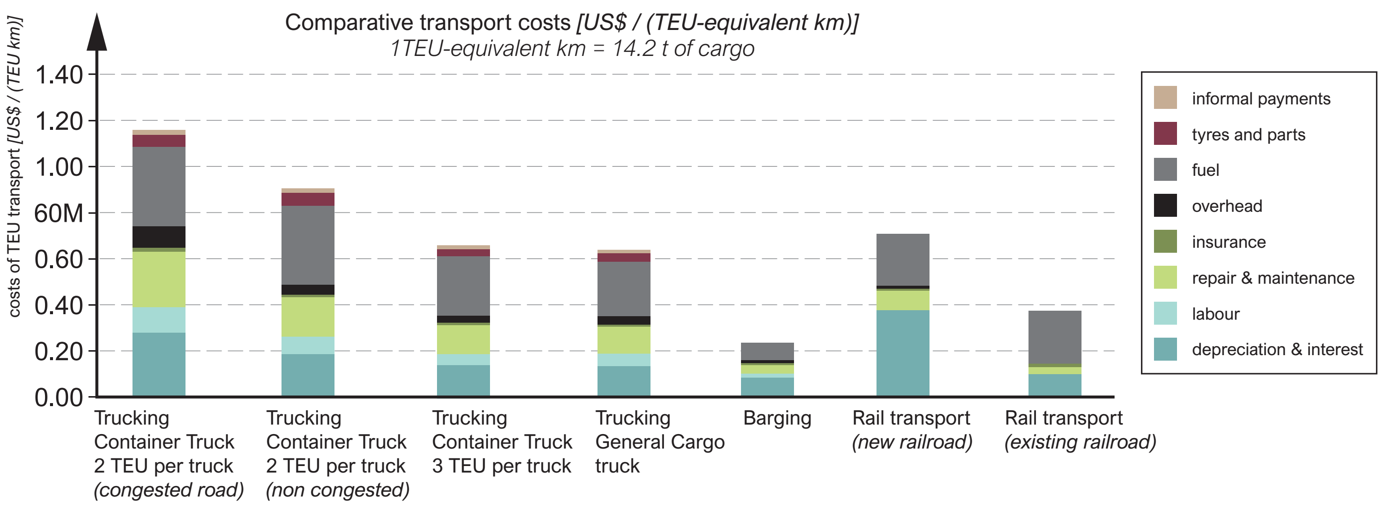

Figure 2.9: Transport costs for the various corridors estimated by logistical modelling (source: Royal Haskoning DHV, image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

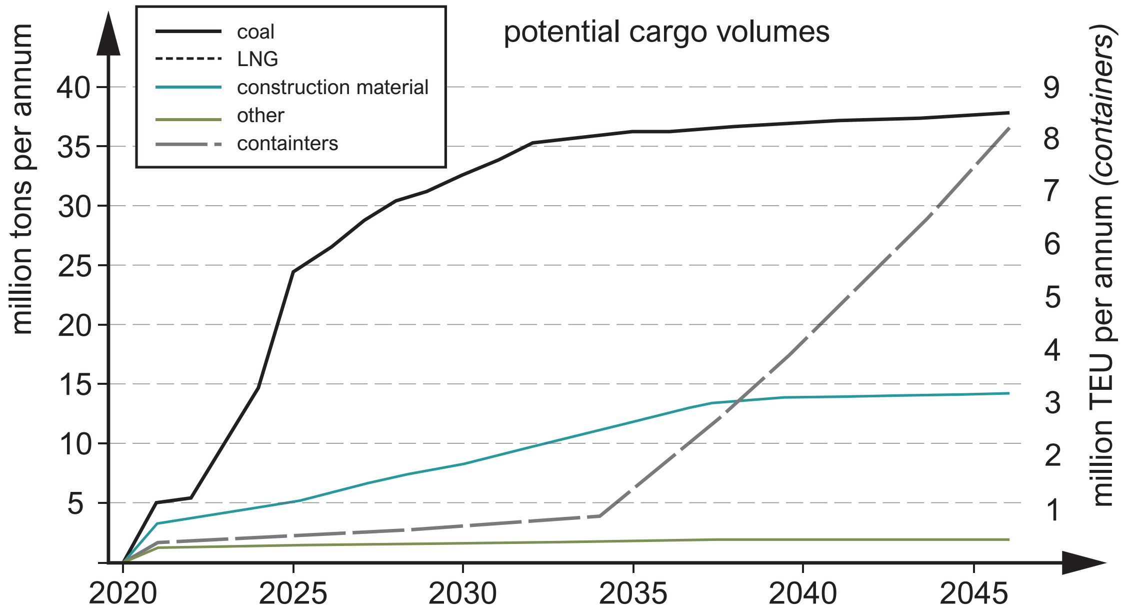

Figure 2.10: Example of a cargo forecast (source: Royal Haskoning DHV, image by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

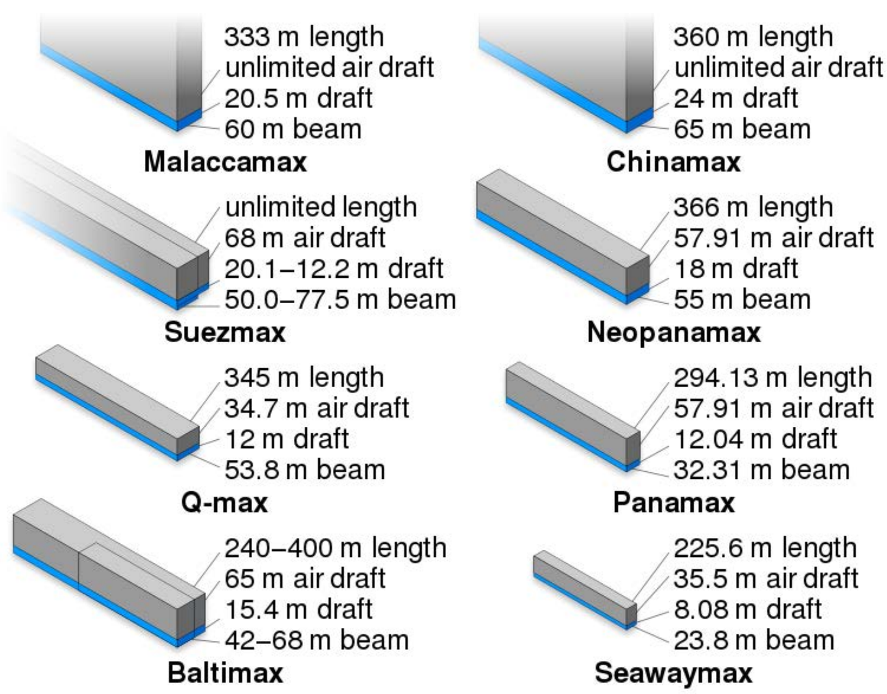

Figure 2.11: Ship measurements comparison of various vessel classes (by Cmglee is licenced under CC BY-SA 3.0).

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.

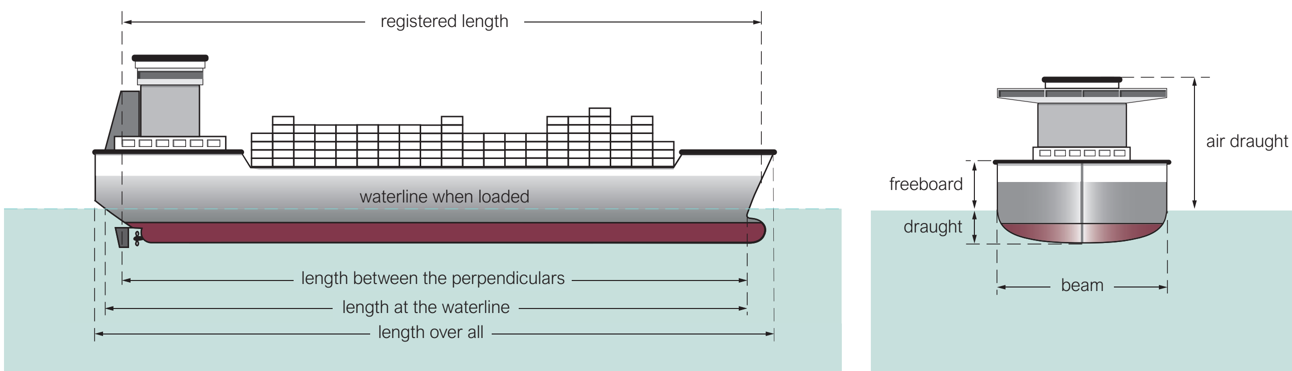

Figure 2.12: Vessel dimensions (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

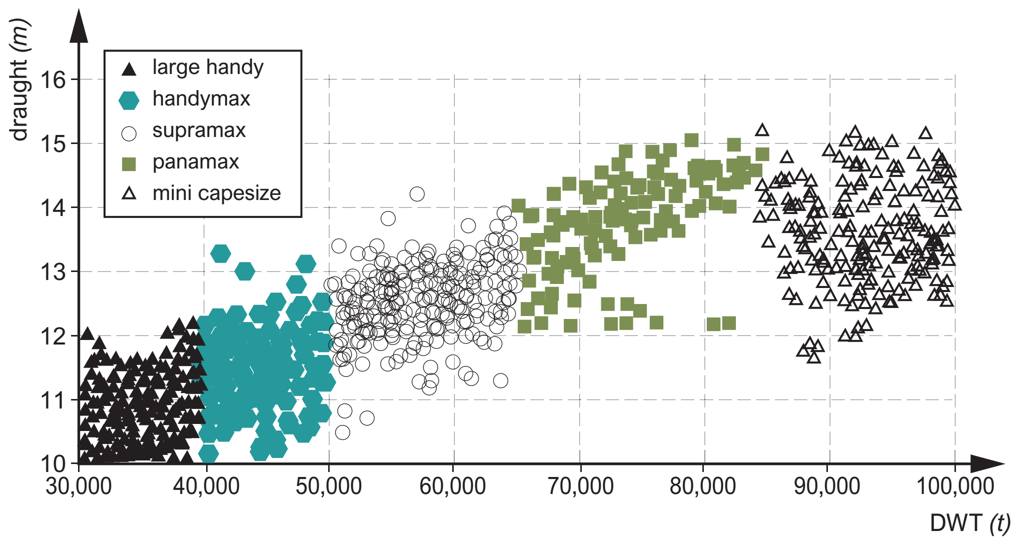

Figure 2.13: Scatter diagram of vessels draughts in various DWT-classes (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

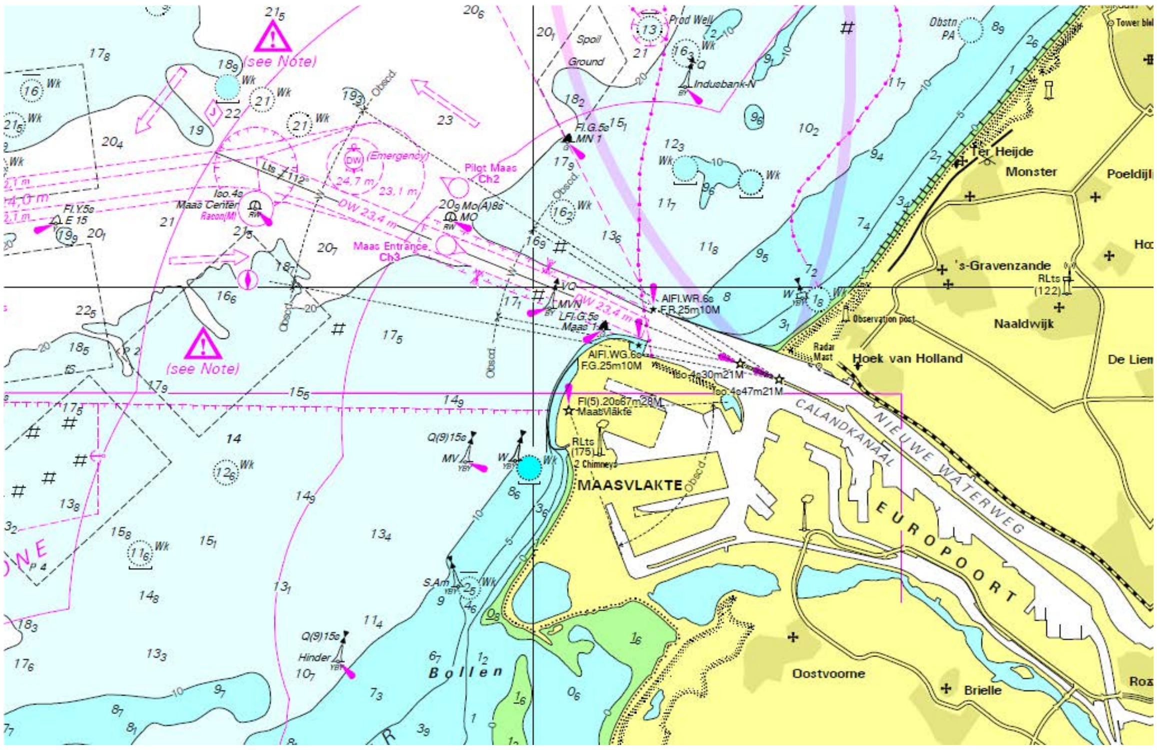

Figure 2.15: Bathymetric map of the North Sea near Hook of Holland (from INT Admiralty Chart 1472 - Bathymetric map of the North Sea near Hook of Holland by the Hydrographer of the Royal Netherlands Navy at Den Haag. Copyright 2019 by Netherlands Ministry of Defence.).

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.

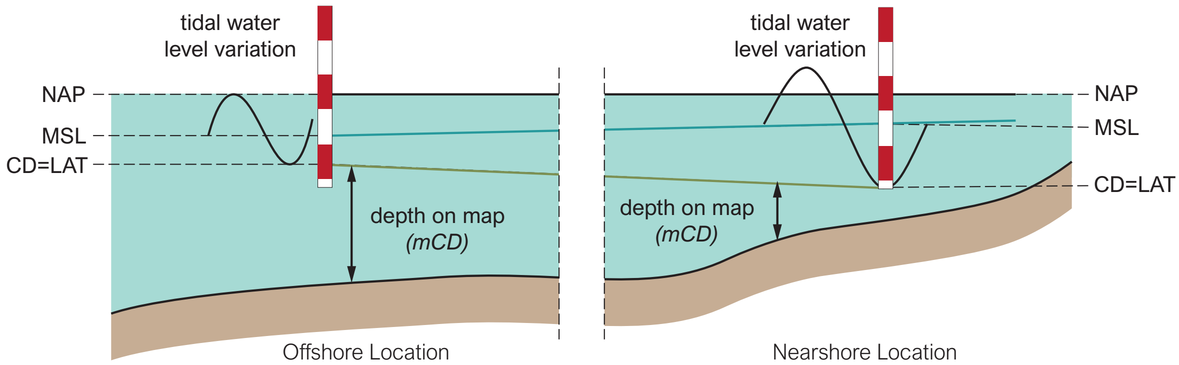

Figure 2.16: Different reference levels may give rise to confusion (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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).

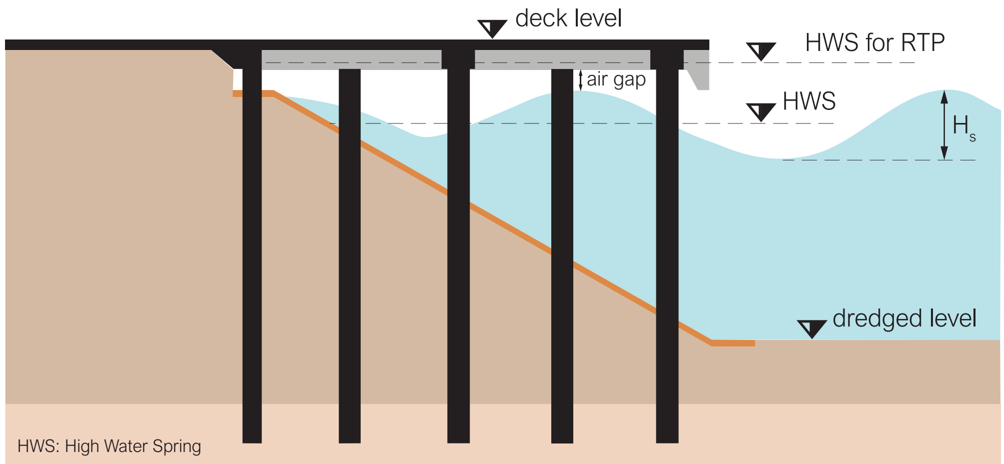

Figure 2.17: Quay deck level and probability of occurrence of the water level (RTP = return period, the inverse of the probability of occurrence) (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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)).

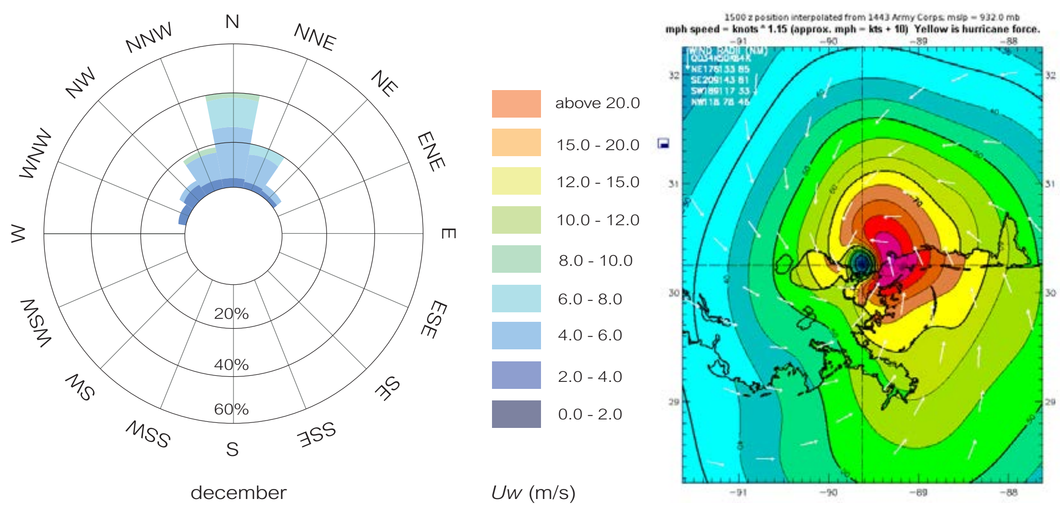

Figure 2.20: Left: example of a wind rose (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0); right: Hurricane wind speeds during landfall of Hurricane Katrina (by NOAA is licenced under CC0 1.0).

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.

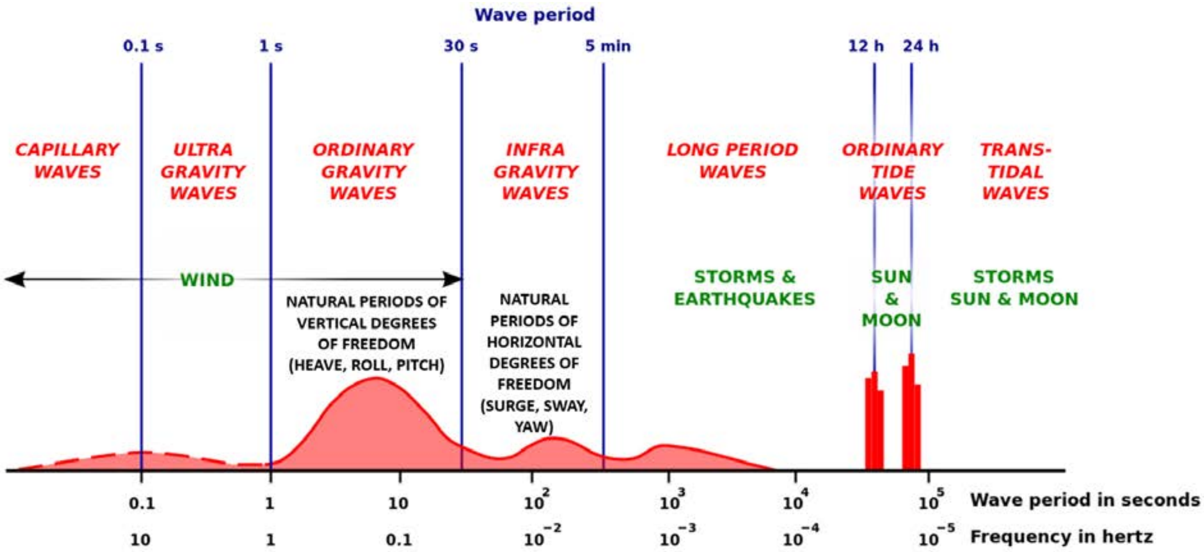

Figure 2.21: Wave periods and eigen periods of vessel motions at berth (adapted from Munk ICCE 1950 by Walter H. Munk is licenced under CC BY-SA 3.0).

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.

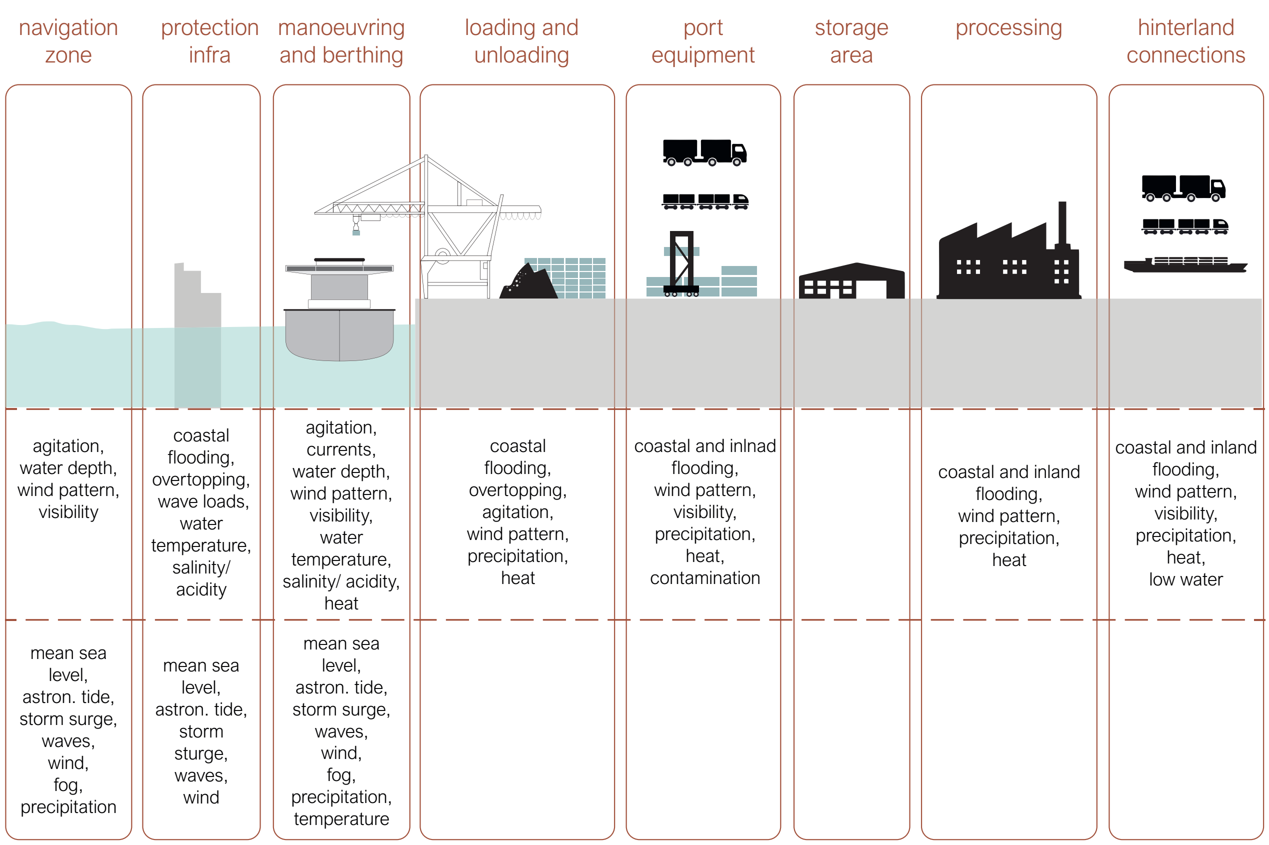

Figure 2.22: Impact of climate change on port development and operations (modified from PIANC, 2019a, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

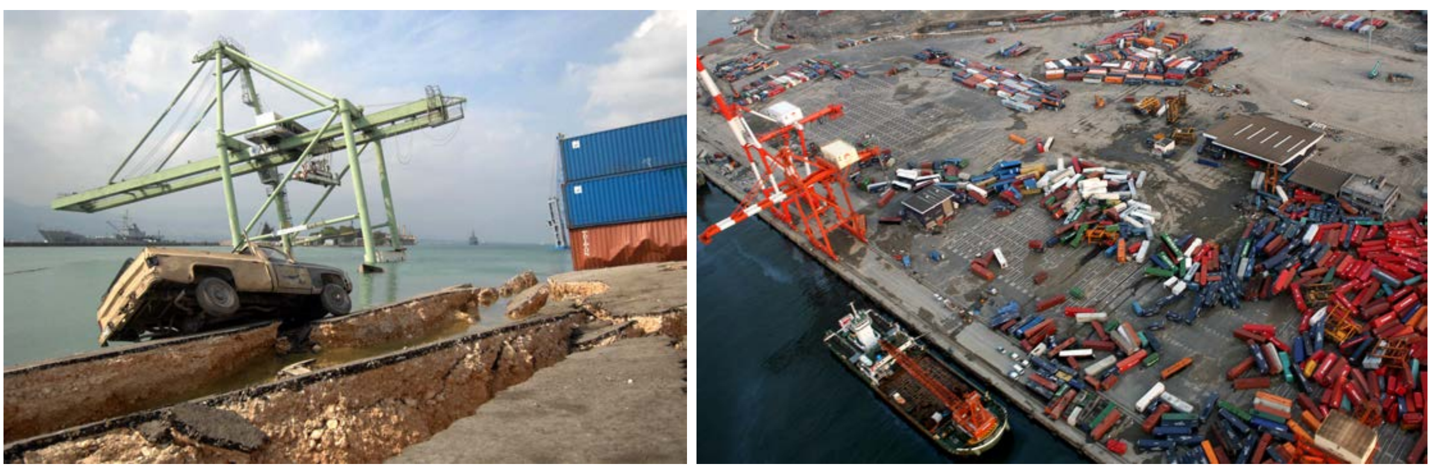

Figure 2.23: Earthquake effects on ports. Left: Collapsed gantry crane, Port au Prince, 2010 (by Chief Mass Communication Specialist D. C. Pearson (U.S. Navy) is licenced under CC0 1.0); right: Earthquake damage at container terminal, Port of Sendai, Japan, 2011 (by Cpl. M. Angel (U.S. Marine Corps)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

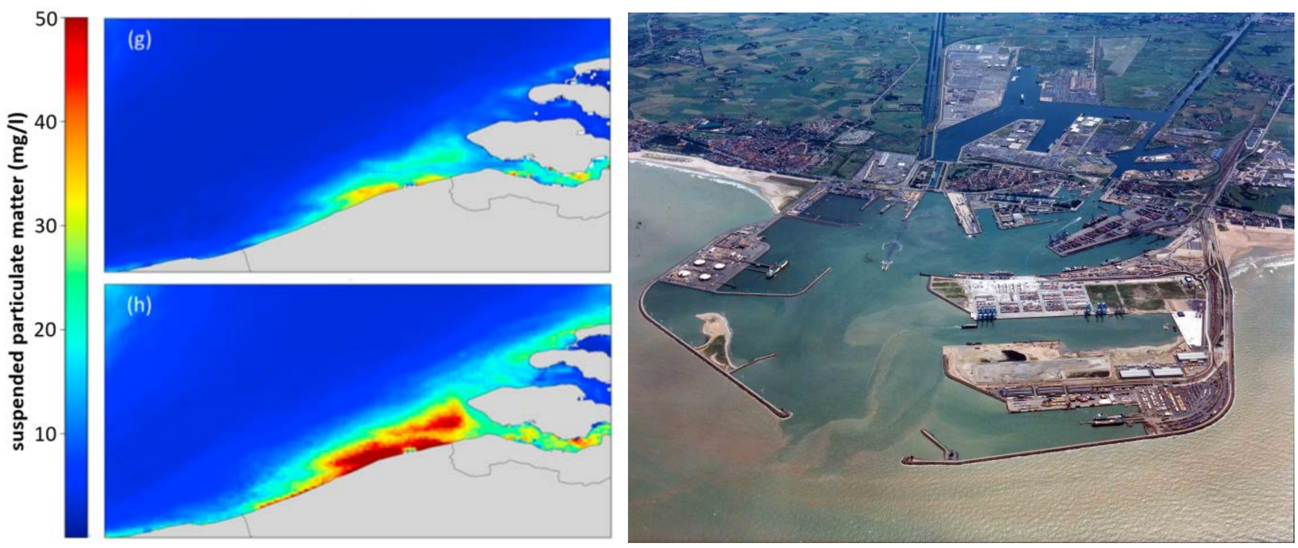

Figure 2.25: Left: observed summer (g) and winter (h) turbidity maxima around the mouth of the Western Scheldt (by Van Maren et al., 2020, is licenced under CC BY 4.0); right: suspended sediment entering the port of Zeebrugge (Port of Bruges-Zeebrugge by antikrot is licenced under CC BY-SA 3.0).

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"