Part IV - Ch 3 Ports and terminals

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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)

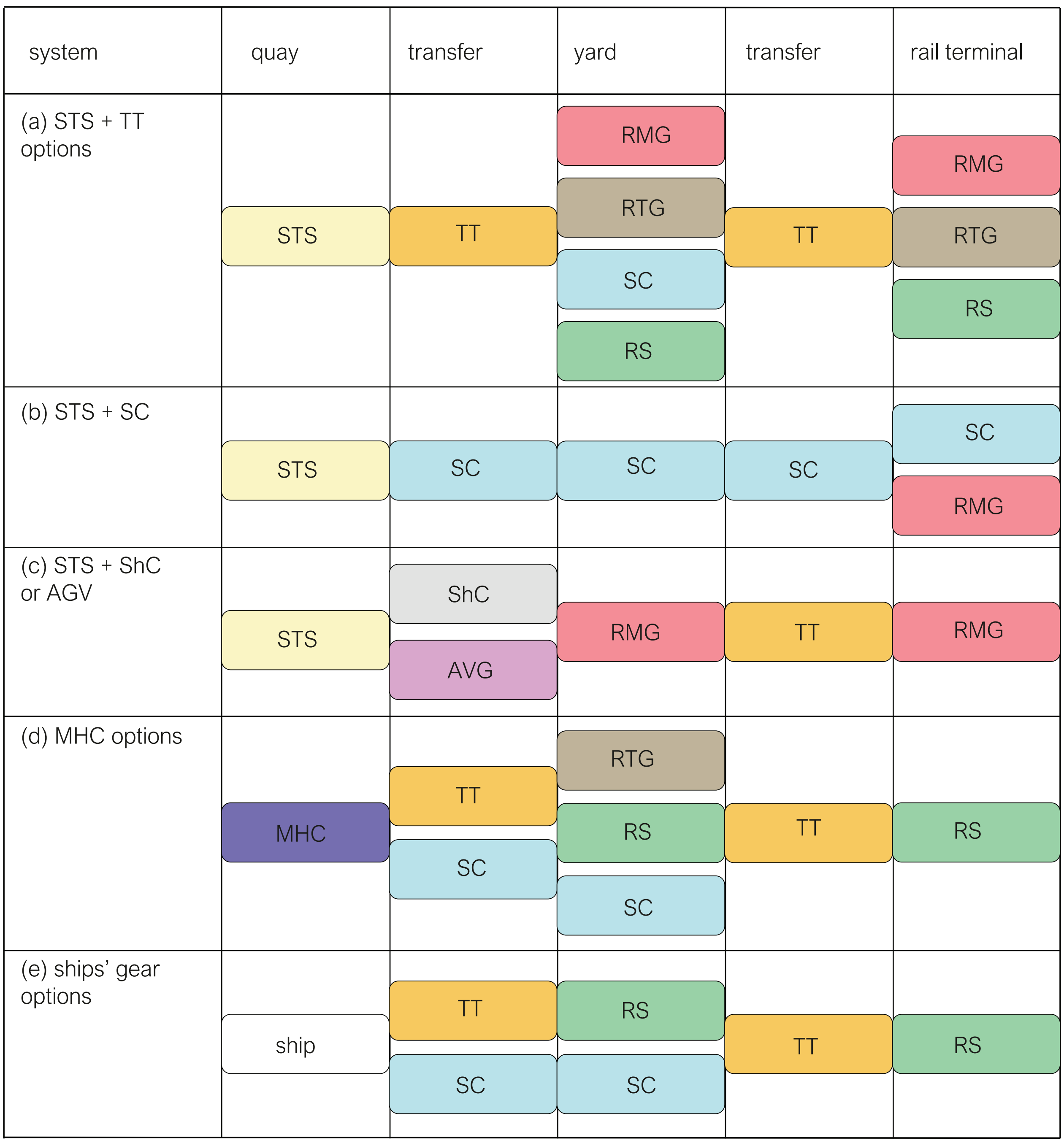

Figure 3.1: Overview of equipment types per quayside crane (reworked from PIANC, 2014d, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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).

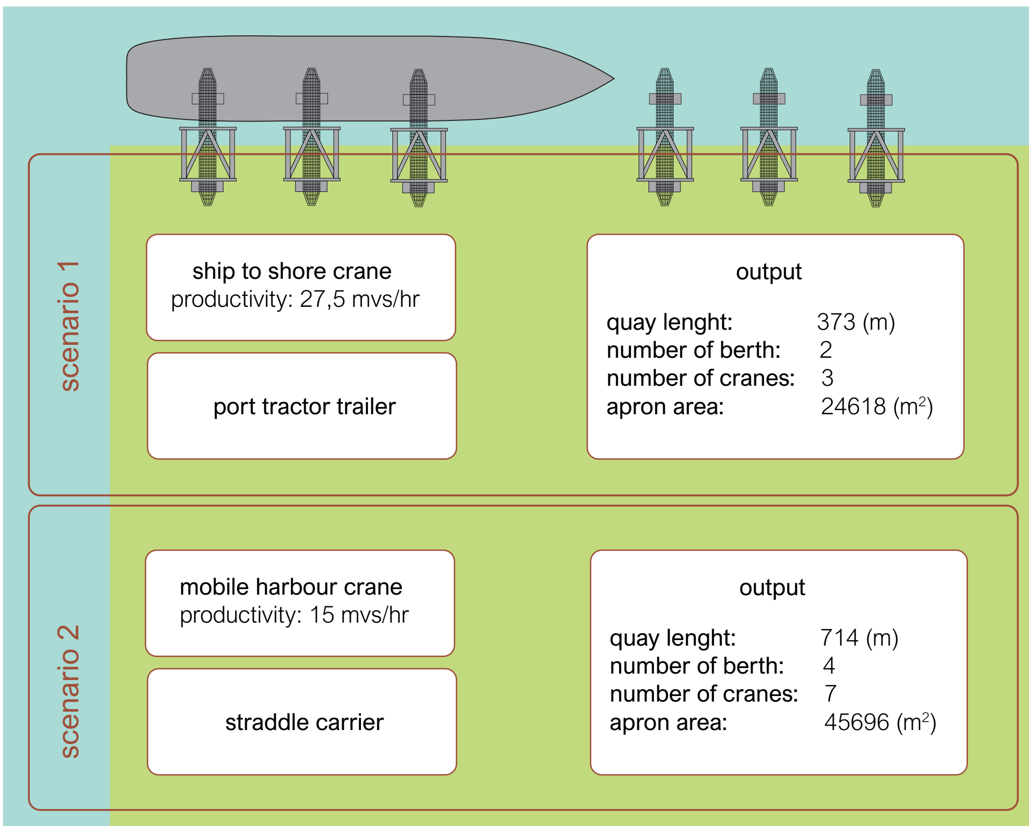

Figure 3.2: Key values for the two case scenarios (reworked from Sharif Mohseni, 2014, by TU Delft – Ports and Waterways is licenced by CC BY-NC-SA 4.0).

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 requirements	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).

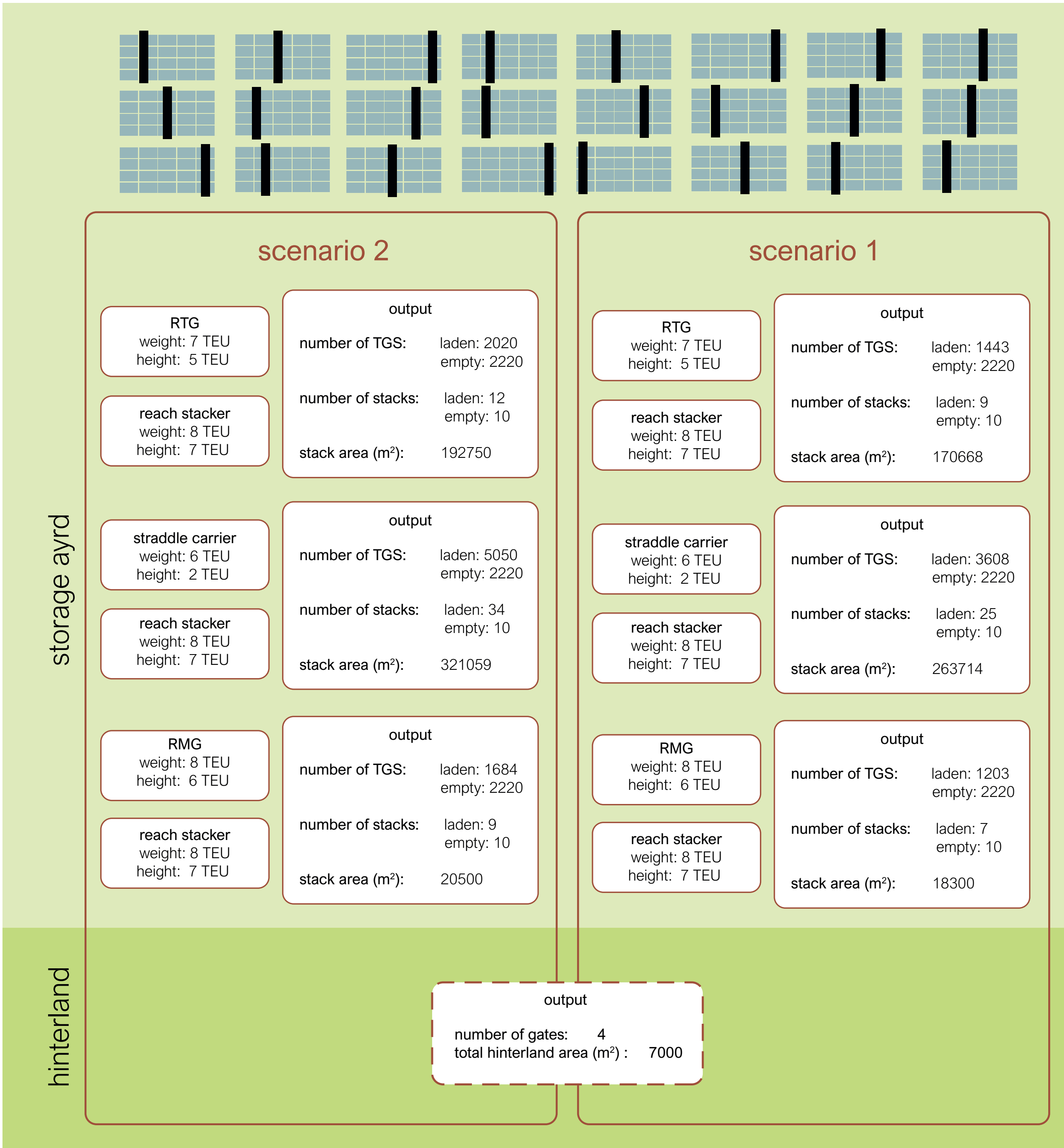

Figure 3.3: Overview of results for the two case scenarios (reworked from Sharif Mohseni, 2014, by TU Delft – Ports and Waterways is licenced by CC BY-NC-SA 4.0).

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.

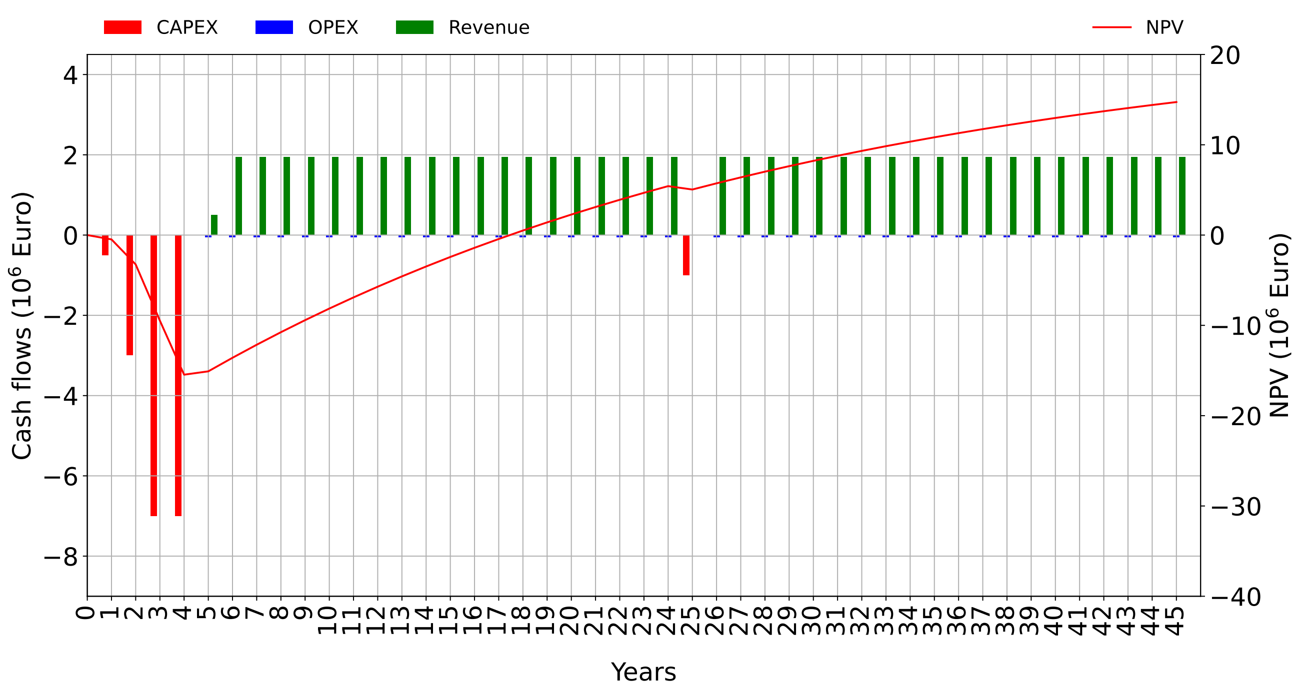

Figure 3.4: NPV calculation 'Base case' (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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€.

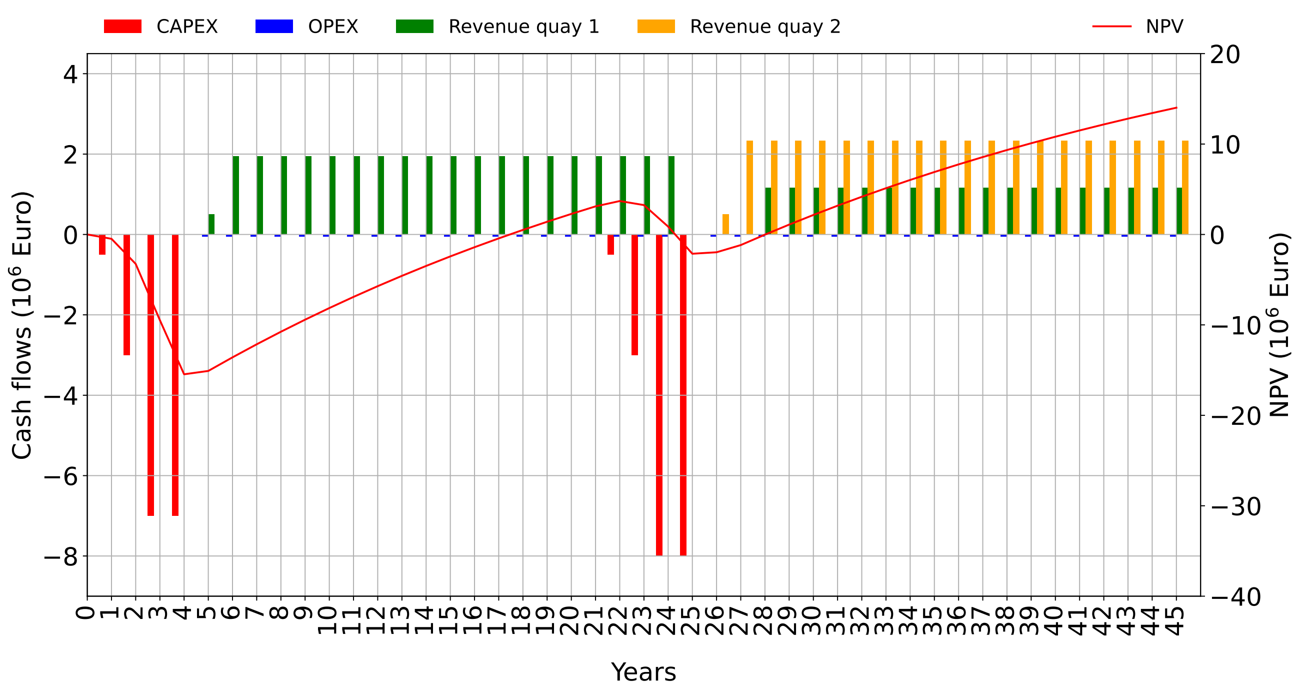

Figure 3.5: NPV calculation Scenario F-1 – 'new quay at a different location' (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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?

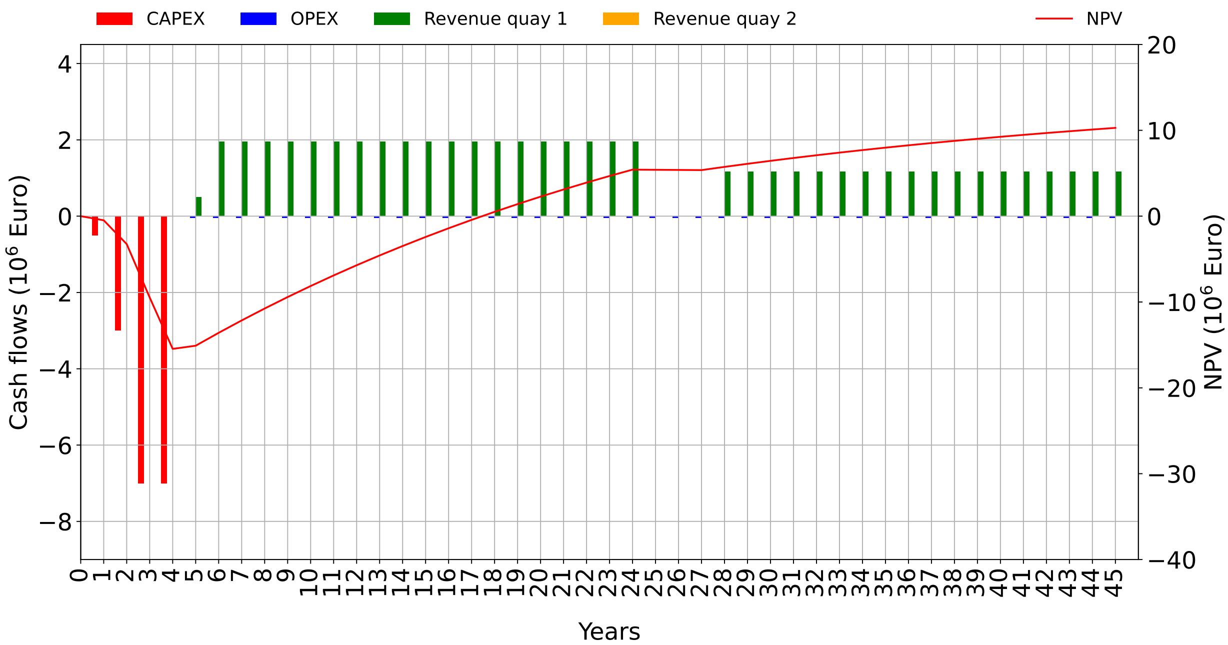

Figure 3.6: NPV calculation Scenario F-1 – 'new quay at a different location', first quay only (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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€.

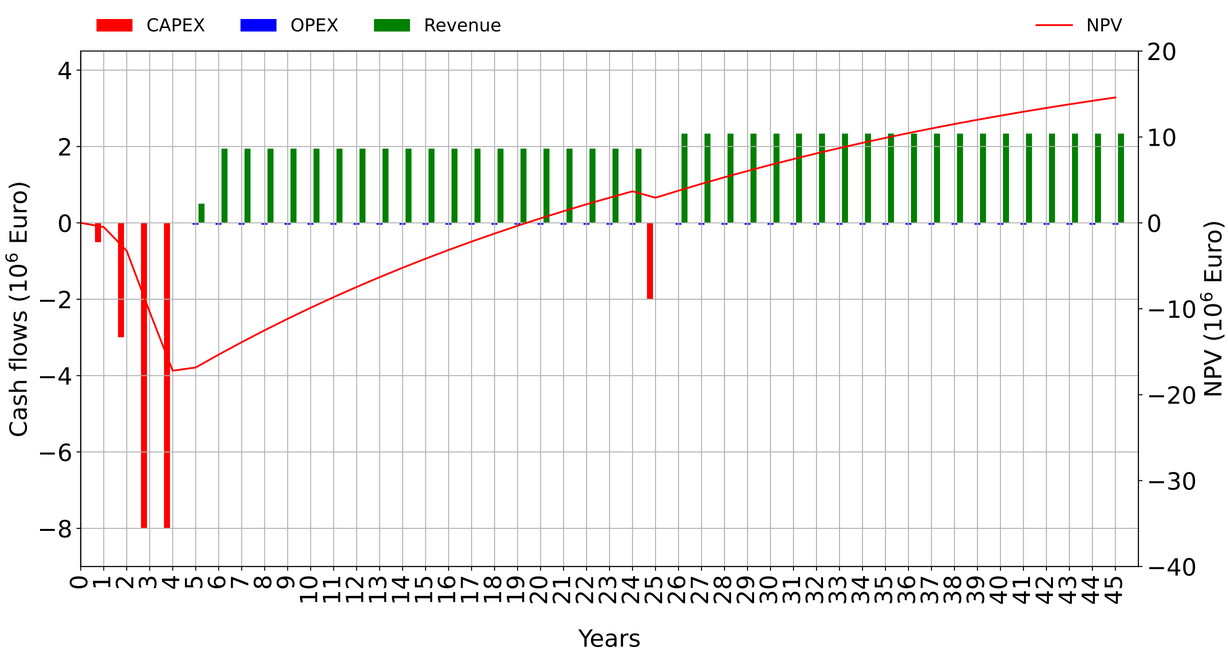

Figure 3.7: NPV calculation Scenario F-2 – 'future proof, robust quay wall' (by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

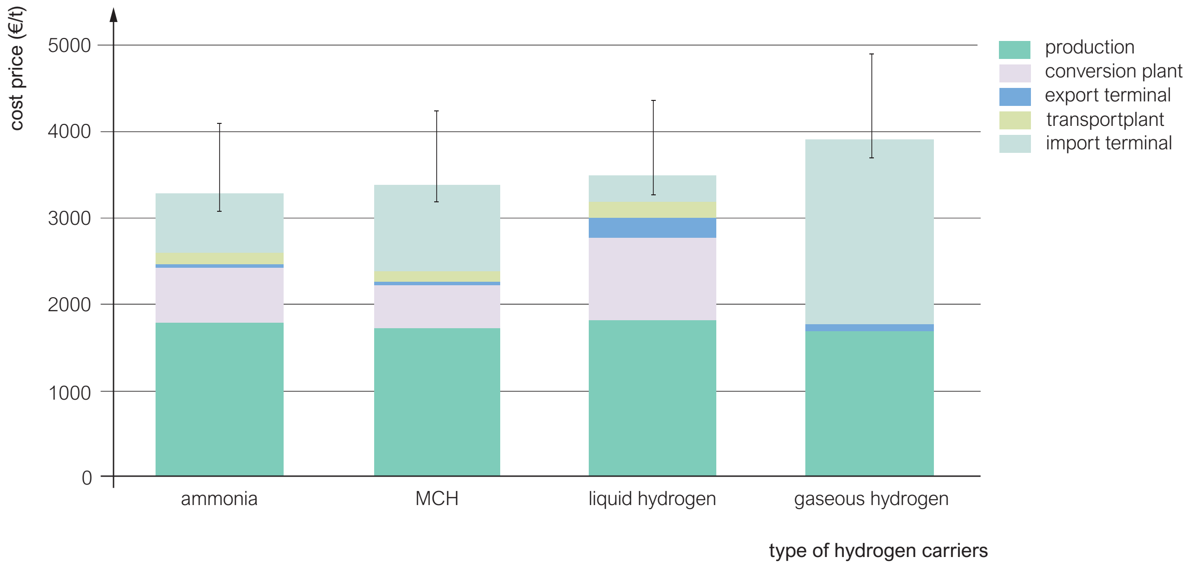

Figure 3.8: Cost price estimate of supplied hydrogen for a demand of 700,000 t/y from Brazil to the Netherlands (reworked from Lanphen, 2019, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.

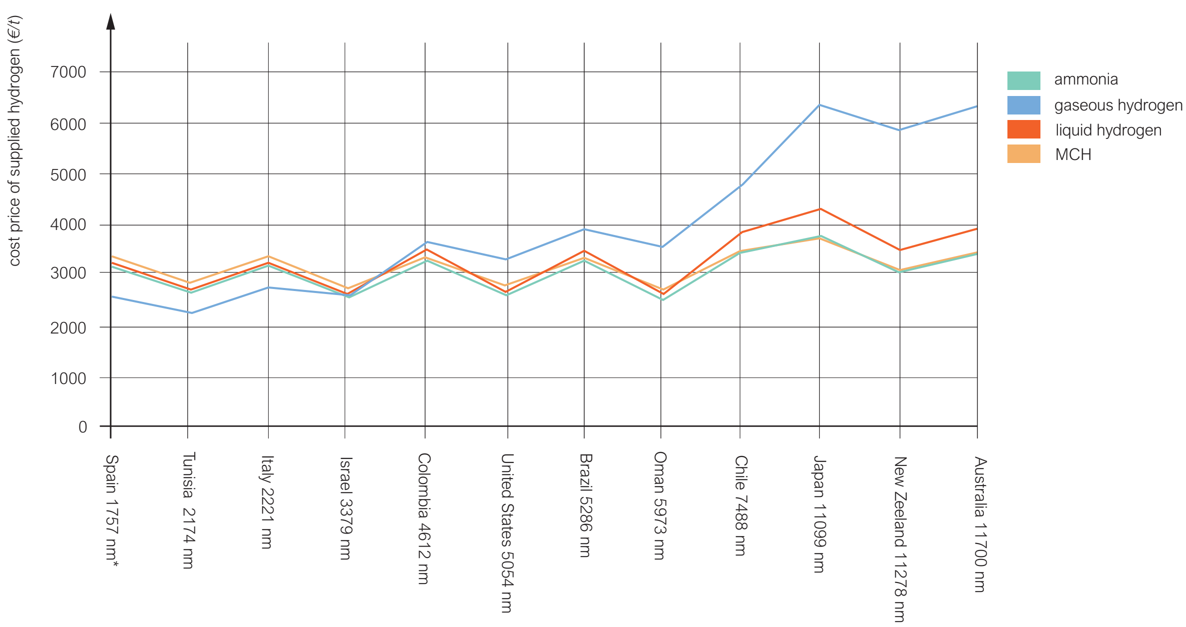

Figure 3.9: Cost price estimate of hydrogen import to Rotterdam from varying with the countries, with a demand of 700,000 t/y (reworked from Lanphen, 2019, by TU Delft – Ports and Waterways is licenced under CC BY-NC-SA 4.0).

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.