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Container ports taxonomy and capacity appraisal of container terminals. Application to the United Kingdom's deep-water container ports system.

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Abstract

This paper addresses how to calculate the capacity of container terminals. Firstly, it is analysed how ultra large container ships (ULCS) have influenced the design of container terminals, and specifically the birth of a distinguished type: the deep-water container terminals (DWCT), which concept is introduced. A classification of container ports and container terminals follows to place the DWCT within a taxonomy. Understanding a container terminal as a system of systems (ship-to-shore, yard-storage, horizontal transfer, receipt and delivery) allows computing the terminal capacity at subsystem level, being the total capacity of the terminal the one of the most constraining subsystem. Finally, the presented methodology is applied to calculate the capacity of the United Kingdom lift-on lift-off deep-water container ports system.

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Keywords: capacity; container; terminals; ports; United Kingdom; calculation;

1. The evolution of containerships and the impact of ultra large container ships (ULCS) on port infrastructure

Seaborne world trade expanded rapidly after World War II, which provoked longer waiting times and frequent congestion at the seaports. The use of containers in sea transport took off as it helped to mitigate congestion issues for its utilisation meant lesser waiting times and efficiency gains, which resulted in increased port capacity. However, the

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introduction of ultra large container ships (ULCS) is causing some diseconomies of scale and inefficiencies at container terminals. Congestion might appear in the container terminals as if they are ill-prepared to handle the peak flows that the handling of ULCS provokes. Container ports' failure to adapt to new generations of container vessels and not being able to cater them efficiently may ultimately lead to traffic diversion.

Ultra large container ships (ULCS, also known as ultra large container vessels, ULCV) are container ships with a capacity exceeding 14,500 TEU. The Emma Maersk container ship can be regarded as the first ULCS. This Maersk E-class containership entered service in August 2006 and until 2012 remained the largest containership ever built. This revolutionary ULCS can carry 14,770 TEU but the carrying capacity came at a price. The ship dimensions, length overall (LOA) 398 m, beam 56.4 m, and especially a 15.3 m draught, meant that at the time of the ship launch, she could only call at few specialised deep-water terminals along the Far East – North Europe main maritime trade route.

Driven by a pursuit of profitability and efficiency gains, the size of container ships has increased relentlessly in the last decades. A breakthrough contribution in the development of container ships was the introduction of a hatch cover-less design. As a result, ships with full height cell guides were built. The advantage is the elimination of the time needed for the removal and placing back of the hatch cover and lashing. Ligteringen and Velsink (2014) considered wrongly that the efficiency gains of this design were meagre and therefore it would not be employed in subsequent book-orders to shipyards. The newest ULCS designs launched by the major carriers, which use a full cellular hatch cover-less design (fig. 1) have proved a successful design concept despite of potential drawbacks such as overcoming seawater in the hold.

Fig. 1. Fully cellular ULCS

There are currently hundreds of ULCS capable of carrying more than 18,000 TEU in operation or ordered (Van Hassel et al., 2016). Shipping companies are keen on ordering these vessels attracted by the cost advantage per slot that the early adopters carriers had since 2006 (introduction of Maersk Triple-E Class).

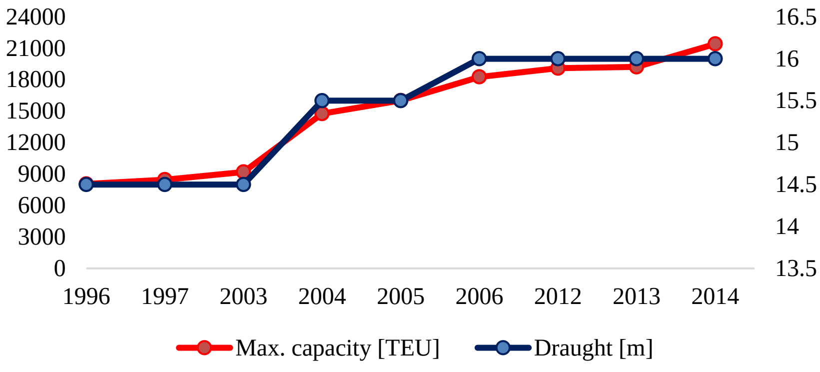

Fig. 2. Evolution of the maximum carrying capacity [TEU] and draught [m] of containerships

The largest ULCS are mainly used in the trade route between the Far East and North Europe via Suez Canal, which is the only route with enough volumes to fill this kind of ships up, thus making them sensitive to use from an economic point of view. Despite of these ships operating usually significantly below its capacity, the liners continue to order them.

As shipping companies have more ULCS units available, older smaller vessels are scrapped or assigned to other routes. This has increased the size and capacity of ships serving secondary routes, which is known as *cascading effect*. This process increases the average size of the containerships that serve these complementary routes (Notteboom and Cariou, 2009). After the concentration phase in the container shipping industry and the push for acquisitions and mergers, it is common that one ULCS is replacing two smaller vessels in certain routes. The immediate consequence of the cascade effect is an overall increment of the average carrying capability of the container fleet, which has translated into pressure for secondary ports to make the necessary infrastructure and superstructure investments to serve them or risk being out of business and losing the traffic volumes (Wilmsmeier and Monios, 2013). The quest for economies of scale using ever-growing ULCSs is not over yet. ULCSs allow for efficiency gains in fuel and reduced greenhouse gas (GHG) emissions per tkm compared with their predecessors. Hub-and-spoke networks that enable economies of density depend on them. Nevertheless, the following factors that could limit the growing size of ULCS:

- Diminishing returns of scale as ships are becoming bigger (Drewry Shipping Consultants, 2018; OECD, 2015; Wray, 2016).
- Physical constraints at choke points. Maritime bottlenecks like the Strait of Malacca (minimum draught 25 m) and the Suez Canal (maximum draught 24 m after the 2015 expansion).
- Pressure on the infrastructure requirements at the ports of call. Container port capacity expansion happens often years before a level of demand is causing congestion to justify the investment. However, bigger ships pose a dilemma to many port authorities and container terminal operators: either they invest in infrastructure to accommodate new vessel sizes or risk being out of business. The design trend of gaining capacity increasing the draught (fig. 2) has dampened in the last years. The latest design concepts for 24,000 – 25,000 TEU ULCS have maintained the draught between 16.0 and 17.0 m, adding capacity by enlarging the LOA and the beam (table 1). This can be understood from the shipping companies' side, as an effort to keep the compatibility of the future vessels with the current container ports capable of handling ULCS, while trying to bring down the economic cost of upgrading the infrastructure for the port owners.
- Operational peaks at ports. The container terminals (CTs) serving ULCS have seen a decrease in the number of calls per year while they need to process more TEUs per call. Lo-Lo operations from ULCS result in volume peaks that strain all the subsystems of a container terminal; in particular the ship-to-shore and storage subsystems. The ship-to-shore system takes longer for the loading/unloading operations from a container ship, what rises berth occupancy and reduces the productivity while the storage subsystem needs to accommodate more boxes in the storage yard. The economies of scale for carriers can result in inefficiencies in the CT subsystems, which potentially create diseconomies of scale for the container terminal operators. Furthermore, the volume peaks create ripple-effects in the transport networks of the port hinterland.

The shipping lines are the clients of the container terminals. For liners, two aspects have crucial importance: the fees and the duration of the call a given port. From the perspective of the shipping companies, the introduction of ULCS also creates challenges:

- Often there are draught and tidal restrictions (e.g. Antwerp, Hamburg, see table 2).
- Some ports are in upstream locations or too closely situated to urban centres (e.g. Antwerp, Hamburg, Southampton, London).
- Berth expansion is often constrained by lack of adjacent land for development and tied by environmental considerations. (Singapore, Southampton, Antwerp). In some ports, there are conflicting interests for the surrounding land. This is the case not only of waterfront development of residential areas but also in mixed ports of space-competing port terminals, such as cruise or car ones.
- Hinterland connectivity issues. The capacity of the road and railway connections is limited and usually cannot be expanded easily.
- Some ports are unable to keep pace with rapid trade growth due to the demanding infrastructure requirements.
- Berth and yard capacity pushed beyond design limits causing insufficient flexibility during peaks and congestion.

- Congestion around the terminal and depot facilities
- Congestion leads to schedule delays and impacts berthing windows at subsequent ports
- The available supply of pilots in the busiest waterways

Ultimately, all the above-mentioned points lead to efficiency and productivity losses. Hence, the growth in size will be more moderate compared with previous decades, but 24,000 TEU will likely not be the final capacity threshold for container ships and it cannot be ruled out that 40,000 TEU ships might be sailing by 2050. The price of fuel will be critical for the pace of this growth. A return to 2014 oil prices would rush another generation of ULCS.

Table 1. Main characteristics of the generations of containerships

Year introduced	Class	Capacity [TEU]	LOA [m]	Beam [m]	Draught [m]
Previous generations					
1956	Early containerships	500 - 800	137 -200	17 - 20	9 -10
1970	Fully cellular	1,000 - 2,500	215	20	10
1980	Panamax	3,000 - 3,400	250	32	12.5
1985	Panamax Max	3,400 - 4,500	290	32	12.5
1988	Post Panamax I	4,000 - 6,000	300	40	13.0
2000	Post Panamax II	6,000 - 8,500	340	43	14.5
2006	Post Panamax III	11,000 - 15,000	397	56	15.5
Current generations					
2010	Post Panamax IV	14,000 - 15,000	353	51 - 53	15.0
2014	New Panamax	12,500	366	49	15.2
2013	ULCS	18,000 - 22,000	400	58 - 59	15.5 - 16.5
Future designs					
2020?	ULCS II Generation	22,000 - 24,500	413	59 - 61	15.5 - 17.0
2025?	ULCS III Generation	24,500 - 26,300	430 - 443	61 - 63	15.5 - 17.0

Table 2. Restrictions in selected European container ports

Port	Draught restriction [m]	Other restrictions
Antwerp	16.0 with tide, incoming; 15.2 with tide outgoing	
Bremerhaven	12.8 (tide-independent); 14.5 with tide, incoming	
Hamburg	11.6 (tide-independent); 13.9 with tide, incoming, 12.4 with tide, outgoing	Turning basin diameter = 450m. Especial authorisation for vessels longer than 335m required, air draught limitations for ACT terminal
Le Havre	14.5	
Valencia	16.0	Length = 400m
Zeebrugge	16.0	

2. Commercial seaports

A commercial seaport is a link in a supply chain that provides both a physical and information interface that allow material and information flows between transport modes. Ports are composed by specialised terminals, which are individual nodes capable of modal interchange between the maritime and terrestrial modes of transport. The storage area acts as a buffer that allows accommodating the different flow rates of container delivery and extraction of the aforementioned modes. A seaport provides an interface between land and water where good and information flows occur. The port facilities permit the harbouring of ships, the loading and unloading of their cargo, the storage of goods, and allow inter-modal exchange with the hinterland and foreland. In the 1980s, ports were still considered homogeneous identities competing with each other at various levels (Verhoeff, 1981). Currently, ports are regarded as links in global logistics chains (Musso et al., 2013; Suykens and Van De Voorde, 1998).

The port market is characterised by high entry barriers such as costly infrastructure, specialised expensive machinery, sunk costs, indivisibility of the infrastructure and economies of scale. For the transportation of the containerised cargo towards a given hinterland, just a few ports compete, acting as the gateway points, so the market is in practice an oligopoly. The structure of the port costs that a vessel must pay for the utilisation of a port is composed, according to Van de Voorde and Winkelmans (2002), of the following terms: cargo-handling, ship's time in port, port dues (or tariffs) and other fees (such as waste fee).

3. Container ports and container terminals

Container ports are link elements in value-driven supply chains (Robinson, 2002) that comprise, at least, one container terminal (CT).

A **container terminal** (CT) is a *system* (Veeke et al., 2008) that provides a transfer interface within a commercial port allowing both material (containers) and immaterial (information) flows between maritime and other transport modes. Thus, two different flows are handled simultaneously in a port terminal: the physical flow of cargo and the information flow. A container terminal reconciles two external interfaces: the quayside (loading/unloading of ships) and the landside (loading/unloading of lorries and trains), thus enabling intermodal exchange (Steenken et al., 2004). The four subsystems composing a container terminal are:

- Ship-to shore subsystem. It constitutes the maritime interface that allows an effective transfer of goods between the container vessels moored at the berthing facilities and the land systems. It uses port infrastructure (quays, apron) and requires specific equipment, such as ship-to-shore cranes.
- Yard-storage subsystem: It is the most demanding subsystem in terms of area in a modern container terminal. The storage area acts as both a link and a buffer between the maritime and other transportation modes.
- Receipt and delivery subsystem. It facilitates the landside nexus.
- Horizontal transfer subsystem. It allows the transportation of freight between the other subsystems. It is not attached to a determined physical zone but includes the technology and machinery enabling physical and information movements.

Container ports rely massively on shipping lines for their revenue generation. In the last decades, container ports have seen their bargain power decreased because of increased volatility due to technological developments. Container ports are especially sensitive to enter the obsolescence phase of their life (Charlier, 2013). If they fail to adapt quickly to new infrastructure requirements driven by new containership designs, traffic flows will divert.

4. Deep-water container terminals (DWCT) and conventional container terminals (CCT)

A **deep-water container terminal (DWCT)** is defined as a container terminal in a seaport capable of berthing ULCS and handling their flows of containers and information. A DWCT needs to have these minimum infrastructure requirements:

a) Related to the ship-to-shore (STS) subsystem:

- Draught at the berth pockets along the quay: at least 16.0 m, preferably tide-independent.
- Entrance channel depth: at least 14.5 m. Normally the draught of the entrance channel is dredged about one to two metres lower than the draught in the berth pockets to reduce the dredging cost. This is possible because ships use the flow (high tide) to sail into the berthing pockets by the quay, then they can safely stay at them in the ebb. The margin between the keel of the ship and the seabed, known as Under Keel Clearance (UKC) is also smaller for berthed ships than it is when they are sailing. This may vary for different ports, especially if the ebb and flow is not of significance (such as in the Western Mediterranean ports).
- Turning basin with at least a 400 m radius.
- Quay length: at least 400 m per berth. The recommendation is to add a 10% of the LOA of the maximum vessel for separation and berthing (Puertos del Estado, 2011). Thus, a minimum of 440 m of linear quay per berth is preferred.

b) Related to the storage subsystem:

- Specialised state-of-the-art machinery deployed in both ship-to-shore (STS) and storage yard subsystems. The STS cranes need to have enough reach to handle the beam of the ULCS. Normally automated rubber-tyred gantry cranes (ARTGs) or automated rail-mounted gantry cranes (ARMGs) are used as storage yard handing equipment for maximum efficiency and productivity gains.
- Sufficient storage yard area (to avoid congestion in the storage subsystem).

The maximum draught of a container terminal is one of the key parameters that determine the role of the terminal within international supply chains. Capacity expansion of maritime infrastructure is a long-term and very expensive process. The dredging works of a harbour to allow a specific water depth along a container terminal quay and its access channel comes at a high economic cost. Hence, it is unlikely that the draught parameter could be modified once the container terminal is built as the deepening of the draught and reconstruction of the quay would involve a substantial investment. The construction process might be even costlier than to build a new container terminal, or at least a deep-water quay, from scratch. In greenfield port development projects, firstly the traffic that the port development aims to capture is forecast. Afterwards, the infrastructure requirements (Table 3.3) to serve that kind of traffic are established reflecting on the container traffic, which the port seeks to capture.
In contrast, **conventional container terminals (CCT)** are those, which do not meet the characteristics reflected in table 3. Therefore, conventional container terminals cannot cater for deep-sea traffic and serve a different kind of container flows, such as feeder traffic and short-sea-shipping (SSS).

Table 3. Deep-water container terminal (DWCT) characteristics

Physical requirements of the infrastructure	Container flow-management requirements (superstructure)
Draught (berth pockets) ($\geq$ 16.0 m)	Specialised STS cranes
Entrance channel draught ($\geq$ 14.5 m)	Yard handling RMG/RTG
Turning basin ($r > 400$ m)	Automation
Quay length ($\geq$ 440 m per berth)	Sufficient storage area

5. Classification of container ports

This section classifies container ports and terminals under different criteria, gathered in table 4.

Container ports can be considered pure container ports if they handle just one category of traffic or mixed container ports if several types of cargo flows coexist in the same port. Examples of pure container ports are London Gateway and JadeWeserPort (Wilhelmshaven). Amongst mixed containers ports we find Southampton (lo-lo, ro-ro, dry bulk and general cargo, liquid bulk, and passengers) and Felixstowe (lo-lo and ro-ro).

Looking at the origin and destination of the goods handled by container ports, they can be categorised into gateway or transshipment ports. A gateway terminal serves primarily its hinterland (e.g. all major UK ports), while in a transshipment port the cargo predominantly both comes and is bound for the port's foreland (e.g. Algeciras, Gioia Tauro). Mixed traffic ports are those that route containers mainly to their hinterland and still handle a significant proportion of transshipment containers (Hamburg, Valencia).

Finally, regarding the ownership of the port assets and the labour factor structure, the container ports can be classified as public service port, tool port, landlord port or private service port using the recommendations of World Bank (2007). A gateway port serves its hinterland acting as the interface between it and the maritime traffic. Therefore, most of its traffic is bound for or comes from the port hinterland. A terminal may attend mainly particular flow of goods while being orientated mainly to export or import. For example, some container terminals in China are almost pure export terminals. A hub is a terminal, which most of its traffic is transshipment. Transshipment cargo comes and is bound for the port's foreland. The containers enter and leave the terminal by sea, so there is no modal interchange. Transshipment terminals have some peculiarities. They normally achieve higher productivity rates and thus have greater capacity than gateway terminals. As they have less land receipt and delivery activity than a gateway terminal, which generates less internal traffic, thus enhancing efficiency. The needs of yard equipment are inferior compared to a gateway terminal. Higher productivity is also explained because of higher amounts of cargo unloaded and loaded per call at port. This permits to employ special spreaders capable of twin-lift and different stowage patterns that allow massive movements of containers.

6. Classification of container terminals

6.1. Classification of container terminals by type of clients they serve

Container terminals can be sorted, according to kind of clients that they serve, as dedicated or common-user terminals. The operations of a common-user terminal are radically different than a dedicated one at the managerial level. A common-user terminal needs to cater for the needs of several clients while keeping in mind their own interests and the port demands. During the last years, port areas have built specialised terminals, to cater for container (lo-lo and ro-ro terminals), liquid bulk, dry bulk, general cargo and passenger terminals. Dedicated container terminals were first introduced in Asia and North America and then in Europe. The first dedicated container terminal was developed by Maersk in the transshipment port of Algeciras (Spain) in the early 1990s (Haralambides et al., 2002).

When public ports bid for tenders to assign a new dedicated terminal, one of the customary conditions is that the terminal reaches a certain threshold of traffic in particular time milestones. This mounts pressure on the terminal operator to work closely with shipping line owners to guarantee steady traffic volumes. Dedicated terminals have become common in the major container ports of Western Europe. They have reached higher productivity levels than the common-use terminals. On the other hand, dedicated container terminals are becoming increasingly part of vertical integration in the supply chains. Shipping lines are becoming increasingly powerful and aim to own container port terminals and even dry ports to vertically integrate and control whole supply chains.

6.2. Classification of container terminals by ownership of the infrastructure

Ownership is another way to classify container terminals. Several models are possible, including public (state) ownership, the concession of the terminal to a terminal operator company (TOC) during a certain period (usually 20-30 years), fully-privatised terminal and joint–ventures between different port agents (port authority, TOCs, shipping companies, etc.).

Table 4: Classification of container ports and terminals

Container ports		Container terminals	
According to:	Classification	According to;	Classification
the type of traffics served at the port	pure container port / mixed container port	the type of clients they serve	dedicated / common user terminal
the kind of container traffic	gateway / mixed traffic port / hub	ULCS berthing capability	deep-water container terminal /conventional container terminal [DWCT / CCT]
the ownership of the port assets and labour factor structure	public service port / tool port / landlord port / private service port	The ownership of the infrastructure	Public /concession (landlord) / fully-privatised / joint – venture terminal

6.3. Classification of container terminals by their deep-water berthing capability

This paper introduces a classification of container terminals in virtue of their capability (or lack of) to berth and accommodate the latest generations of container ships (see table 4) in-deep water container terminal (DWCT) or conventional container terminal (CCT). Table 4 sums up the possible classification of container terminals and figure 3 reflects on the hierarchy between container terminals, container ports and port ranges.

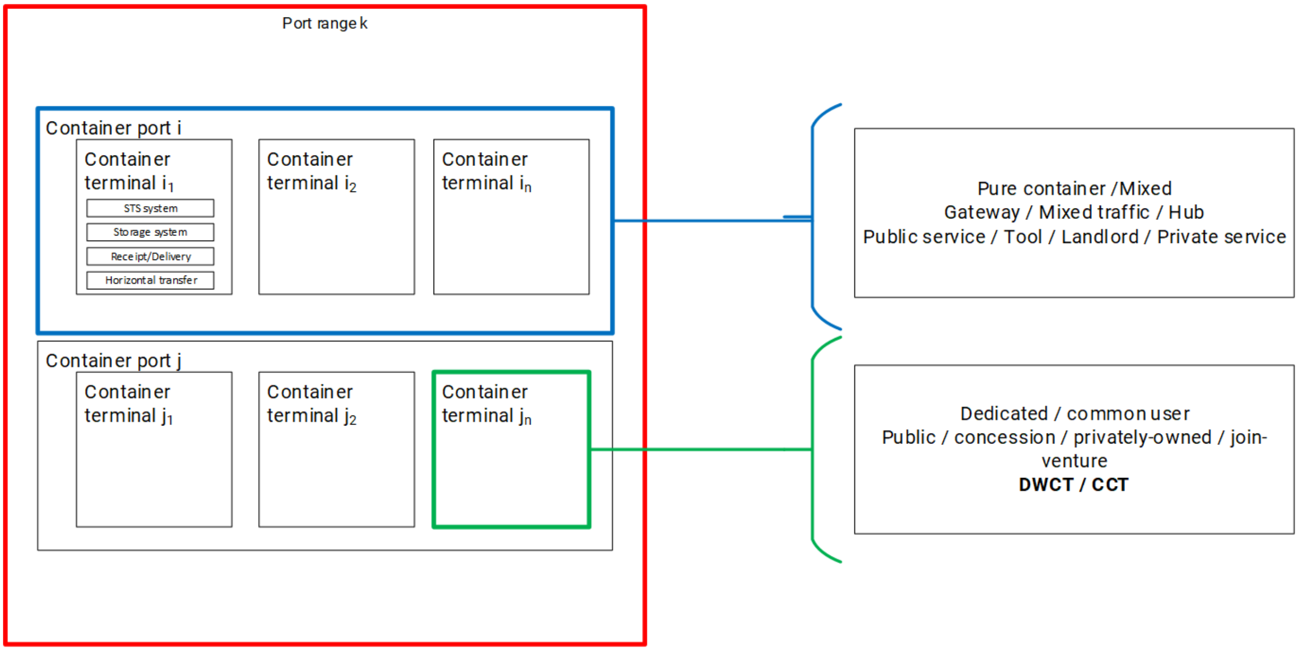

Fig 3. Types of container ports and container terminals

7. Appraisal of port capacity

Capacity is an important characteristic of transport infrastructure. It denotes the capability of the infrastructure to accommodate flows (freight and/or passengers) at a certain cost and service time level. (Bichou, 2009) defined theoretical or designed capacity as the technically maximum possible utilisation rate that can be obtained in the short-run with the existing port facilities and resources (infrastructure, equipment, labour, technology, etc.).

Port capacity can be calculated by using both empirical and analytical methods. Empirical methods are used when a new container terminal is designed and the data required for the application of other methods is not available. Analytical methods use mathematical modelling to evaluate the processes within a port subsystem. Capacity calculation is an essential terminal planning tool as it not only establishes the theoretical capacity limit of the terminal but allows its incorporation to different scenarios in order to analyse how the terminal would respond under them the constraint and condition sets defined in each one.

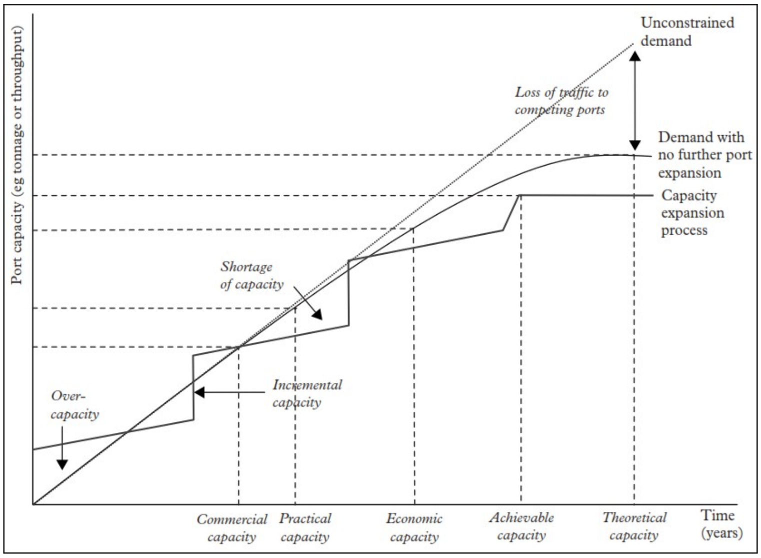

Fig. 3. Different definitions of port capacity according to Bichou (2009)

A container terminal has been defined as a system comprised of four subsystems, namely: ship-to-shore, transfer, storage, and delivery and receipt. Given this characterising of the container terminal, the capacity of the terminal will be the lowest of the capacities of the four subsystems. For the purpose of calculating the capacity of the terminal, a hypothesis is introduced that neither the transfer nor the receipt subsystems provoke bottlenecks that constrain the total capacity of the container terminal. Therefore, in the following sections, a methodology is developed for the calculation of the ship-to-shore subsystem capacity and the storage subsystem capacity. Finally, this methodology is applied to calculate the maximum theoretical capacity of the UK deep-water container ports.

7.1. Ship-to-shore subsystem capacity calculation

The following aspects must be considered when calculating berth capacity:

- Forecast of the traffic that will be handled in the terminal.
- Statistical distribution of both the ship characteristics (in particular draught and length) and their arrival time.
- Parameters that define the quay berth alignment (draught and length).
- Statistical distribution of the service time.
- Number and typology of quay cranes.
- Quay cranes productivity (TEU/hour; tonnes/hour; units/hour).
- Quality of service, which is linked to the relative waiting time deemed acceptable.
- Operational time of the terminal per year.

The annual ship-to-shore (STS) capacity of a container terminal (CT) can be calculated multiplying the number of berths, the berth occupancy ratio, the operational hours per year and the average vessel productivity per hour while the ship is at berth:

$$K_{STS} = \mathrm{n}\phi t P$$

Where:

- K_{STS} : Capacity of the ship-to-shore system of the container terminal per year [TEU/year].
- n: number of berths of the terminal.

- ϕ : Acceptable berth occupancy ratio. This depends on the number of berths, relative waiting time (ratio between waiting time and service time (Tw/Ts), and the definition of arrivals and service times.
- t: Annual operational hours of the container terminal. This depends on the number of days the port operates and working conditions (shifts per day, hours per shift, holidays, etc.) and weather conditions.
- P: Annual average productivity of vessel at berth. It is the ratio between the annual volume of handled goods and the aggregate of the estimated annual gross times during which vessel is at berth (gross berth times). This factor depends on the number and operational productivity of equipment. It also depends on other parameters such as the skills of operators or the connection with the other subsystems involved, etc.

7.1.1 n : number of berths

The number of berths (n) is a function of the length of the berths, the length of a standard vessel that will call at the terminal and the berthing gap, also called ratio of separation (C_{gap}). Therefore, n can be calculated as:

$$n = \frac{\text{lenght of the quay alignment}}{\text{length of standard vessel} \cdot (1 + C_{gap})}$$

There is no unique definition of standard vessel in the literature. Rodríguez (1977) proposes the utilisation of the average length. Other possibility is to use extreme vessels (those whose length is exceeded by 15% of the arrivals). Once determined, the length of a standard vessel needs to be increased by a coefficient C_{gap}. The berthing gap can be assumed to be 10% of the length overall (LOA) of the ship. or a fixed value (e.g. 20 m). The Spanish ROM (Design and construction of Berthing & Mooring Structures) advises to use a safety distance of at least 30 m if the LOA is greater than 300 m and 25 m if the LOA is between 201 and 300 m for the most common configurations of several berths allocated continuously along the same quay alignment (Puertos del Estado, 2011).

In certain cases, such as the construction of a new port or terminal, there is a lack of available information on length and service time distribution. In this scenario, the information of the expected vessels in the terminal should provide a reasonable estimation of the length.

7.1.2 φ : berth occupancy ratio

The berth occupancy ratio represents the degree of congestion of the berths of a container terminal. The berth occupancy ratio can be calculated using queuing theory or simulation models. Under the latter approach, the container terminal can be considered as queue system with n service points (berths). The queue systems is defined by the distribution that models the vessel interval arrival time probabilities (f_1), the distribution that reflects the service time probabilities (f_2) and the number of berths n, which define the queue system (f_1/ f_2/n), using the notation developed by Kendall (1953) and Lee (1966). The distribution functions can be exponential (Markov, Poisson, random), Erlang of order K (E_k), constant (D), hyper-exponential (H) or of any other kind (G).

For the specific case of container terminals, the literature recommends the utilisation of different probability distributions, discriminating between public and dedicated container terminals.

- Private terminal. (E_k/E_k/n). These dedicated terminals are operated by private companies with tightly scheduled calls. The interval time distribution is less random. Some scholars model the arrival time distribution as random (Kuo et al., 2006; Obrer-Marco and Aguilar, 2014) while Agerschou (2004) advises the utilisation of a Erlang distribution of order two.
- Public terminals (M/Ek/n) (Common-user terminals). The distribution of inter-arrival times follows a random distribution whereas the service times are better suited to an Erlang distribution of order K. For public container terminals a value of K of 4 or higher should be considered (E4).

It must be noted that the acceptable berth occupancy ratio (φ) is linked to a number of berths (n). Depending on what system of probability distribution functions has been chosen to define the terminal (f1/ f2) the quality of service (linked to the relative waiting time (Tw/Ts) will vary. In other words, for a given relative waiting time, different values of the acceptable berth occupancy ratio will be obtained depending on the assigned queue system and number of berths.

According to Agerschou (2004) the relative waiting time in a container terminal should not be greater than 0,10. This is coherent with the interval (0.05 - 0.20) for the same ratio proposed by Thoresen (2014). Table 5 shows the impact of the chosen queue system and number of berths in the occupation rate for a level of service linked with a relative waiting time of 0,10.

Table 5. Acceptable berth occupancy ratio φ

	$T_w/T_s = 0.05$			$T_w/T_s = 0.10$			$T_w/T_s = 0.20$		
n	M/E_2/n	M/E_4/n	$E_2/E_4/n$	M/E_2/n	M/E_4/n	$E_2/E_4/n$	M/E_2/n	M/E_4/n	$E_2/E_4/n$
1	< 5	7	22	12	14	31	21	24	43
2	25	27	43	33	36	53	47	49	63
3	38	39	53	49	49	63	60	61	72
4	47	47	61	56	57	70	66	68	78
5	53	54	66	62	63	73	71	73	81
≥ 6	57	58	69	66	67	77	74	76	84

P: Annual average productivity of berth vessel

The annual average productivity of berthed vessel is the division between the annual output (TEU movements) and the sum of the gross berth times. The traffic includes both containers with the port hinterland as origin or destination and the transshipment movements (loading/unloading).

P depends on the average number of cranes used, their productivity and the idle time. It should be stressed that the productivity is gross, therefore it includes the idle time of the ship at berth. It should not be confused with net productivity, which only considers the sum of net times at berth. Obviously, net productive values are always higher than gross ones, as the aggregated time is lower.

An interesting consideration is that the annual average productivity (P) is affected by the average size call. The bigger the average size call is, the higher the productivity that can be achieved. At the same time, the productivity required to serve a large ship is bigger as well. This means that the increase of the size of container vessels due to the introduction of ULCS in certain trade routes and the subsequent cascade effect strain the port ship-to-shore system, as it imposes higher productivity need to the terminal due to the need to load and unload a higher volume of containers in the minimal possible time. In theory bigger average call sizes should improve productivity. However, a recent study by JOC (2017) has found weaker quayside productivity on ULCS compared with mid-size container vessels/ The drop in productivity on ULCS larger than 14,000 TEU is due to larger crane cycles. These ships need higher spread hoists and longer trolley distances on ships that have more than 19 containers across compared with a mid-size containership, which has between 13 – 19 units across the beam.

7.2. Capacity of the storage subsystem

A brief literature review on capacity evaluation for the container terminal storage system has shown two approaches to calculate the handling capacity of a container yard. Frankel (1987), Hoffmann (1985) and UNCTAD (1985) calculated the capacity of the storage subsystem using a demand-based approach. Some of the chosen variables are

$$K_y = (C_p \cdot A \cdot T_{dw}) \cdot \frac{1+F}{360}$$

throughput (understood as number of containers handled per year), dwell time (differentiating between import, export or transshipment containers), the yard equipment, the height of the container stacks and the peak factor. Hoffmann (1985) suggested the following equation to calculate the area of the yard that meets the expected demand:

In Frankel (1987), the following expression was proposed, incorporating the standard deviation of dwell time and the economical utilisation of the storage area.

$$K_y = \frac{C_p \cdot A \cdot (T_{dw} + 2)}{365 \cdot Z \cdot 10^4 \cdot (H + 2h) \cdot U}$$

The supply approach evaluates the number of containers that a container yard would process given the yard area. For Dally (1983) the annual yard capacity (TEU/year) over a given period is calculated using this equation:

$$K_c = \frac{GS_T \cdot H \cdot W \cdot T}{T_{dw} \cdot F}$$

Dharmalingam (1987) modified slightly Dally's equation incorporating some results from several case studies, obtaining equation 3.6:

$$K_c = GS_A \cdot (0.6 \cdot S) \cdot (T/T_{dw})$$

where:

- Ky: required container yard capacity.
- C p: projected container volume (TEU)
- A: area per TEU.
- Tdw: average dwell time in the container yard.
- F: peaking factor
- Z: storage utilisation factor.
- H: average expected stack height by the average number of containers in used stacks.
- h: standard deviation of stack height.
- U : total area utilisation.
- Cc: container capacity (per year)
- GSA: available ground slot.
- GST : total ground slot.
- S: ground slot utilisation factor.
- T : number of days per year.

Finally, Itsuro (2001) proposed the following expression to estimate average dwell time (D) for all container transit through the container yard.

$$D = [\mu D_t + (1-\mu) D_e + (1-\mu) D_i]/2$$

The maximum annual container handling capacity Cmax is computed as:

$$C_{max} = \frac{365 \cdot 2 \cdot C_s}{\frac{\mu \cdot D_t}{H_t} + \frac{(1-\mu) \cdot D_e}{H_e} + \frac{(1-\mu) \cdot D_i}{H_i}}$$

where:

- Cs is the total number of ground slots.
  μ is the transshipment ratio.
- Dt , Di, De average dwell times of transshipped, import and export containers respectively.
- Ht , Hi, He stacking height of transshipped, import and export containers respectively.

7.3. A method for the calculation of the storage subsystem capacity

This section defines a method for the calculation of the storage subsystem capacity in a container terminal. Firstly, several needed concepts for storage capacity calculation are defined.

- Terminal area (AT) [m^2]: Area within the fences of the facility.
- Storage area or yard (AY) [m^2]: Area of the terminal used for the storage of containers. It comprises the area used for storage infrastructure, such as aisles, equipment, rails, etc.
- Ground Slot (GS) [units]: Number of ground TEU slots in the terminal yard. It can be considered that the footprint of a TEU is 15 m^2. This is value proposed by UNCTAD for the access requirement regardless of the handling system.
- Slot: Any possible position in a 3D space that a container can occupy in the terminal yard.
- Net Storage Area (ANY) [m^2].Terminal area used strictly for storing containers. Only the area occupied by ground slots is used for its calculation, without considering the space taken up by storage infrastructure.

$$ANY = GS \cdot 15m^2$$

- Terminal area density DT [GS/m^2] Number of slots per total terminal area.
- Storage area density. DY [GS/m^2] Number of slots per storage yard area. DY = GS/AY
- Tdw [days]: Average dwell time of the containers in the storage yard of the terminal.
- Average number of turnovers per year: 365 / Tdw
- λ : is an operational factor that ranges from 0.55 to 0.70 (Rijsenbrij and Wieschemann, 2011). The operational factor λ reduces the maximum height in order to avoid to have to reposition an excess number of containers.

The annual yard capacity Ky considers the area density, the average stacking height h and the annual turnover of containers. Thus, the annual yard capacity Ky can be calculated as:

$$K_y = GS \cdot h \cdot \frac{365}{T_{dw}}$$

The equation can be reworked introducing the operational factor λ :

$$K_y = GS \cdot H \cdot \lambda \cdot \frac{365}{T_{dw}}$$

Where:

- Ky: Annual yard capacity of the terminal (TEU/year).
- GS: Number of ground TEU slots in the terminal yard.
- H: Maximum height of stacks or nominal height of the yard equipment.
- Tdw: Average dwell time of the containers in the storage area (in days).
- λ : Operational factor.
- 365/Tdw : Average number of turnovers per year.

As the container terminal has been defined as a system of systems, the capacity of the terminal will be the lower capacity of the ship-to-shore and storage systems. Once that the container terminal annual yard capacity is calculated using the previous equation, it is needed to apply a transformation coefficient (C_{YTS})to compare this value with the ship-to-shore system capacity obtained. This coefficient accounts for transshipment containers being counted twice in the ship-to-shore system. The transformation coefficient can be calculated as:

$$C_{YTS} = \frac{2}{2 \cdot HI + TS}$$

Where:

- HI: ratio of traffic with origin or destination the port hinterland over total traffic.

- TS: transshipment ratio over total traffic.

The expression can be reworked to be expressed only as a function of the transshipment ratio (TS):

$$C_{YTS} = \frac{2}{2 - TS}$$

Finally, the STS-equivalent annual yard capacity ($K_{Y,eq}$) is given by:

$$K_{y,eq} = C_{YTS} \cdot K_y$$

8. Estimation of the UK DWCP system capacity

The storage subsystem capacity of the UK deep-water container ports (Felixstowe, Southampton and London) has been calculated using the proposed equation. The values for A_T and A_Y have been obtained measuring the surfaces directly on Google Earth software (fig. 4). Then, the number of ground slots (GS) can be estimated. A value of λ = 0.6 has been used, and the T_{dw} has been considered to be six days. The values for the operational average stacking height have been extracted from table 6. Table 7 collates the yard storage system capacity results for the UK container port system.

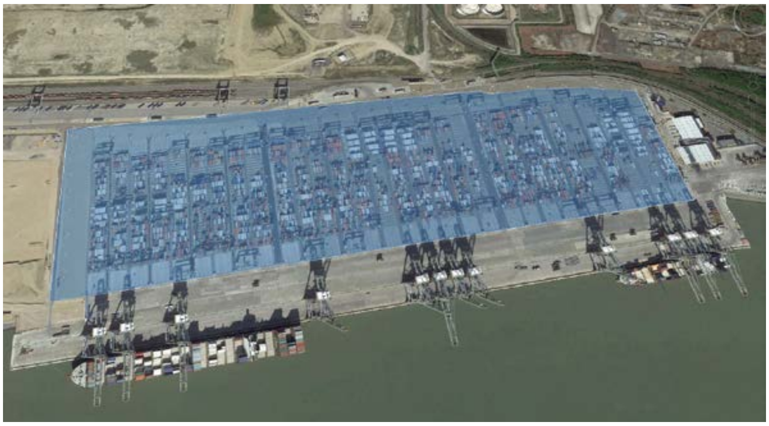

Fig 4. Calculation of London Gateway's AY (Map: Google Earth)

Table 6. Area density, operational average stacking height and static capacity of container terminals according to type of equipment

Equipment	Stack wide	Stacking height	D_y (GS/ha)	Operational stacking height [m]	System density or static capacity (C_s) [TEU/ha]
Chassis	-	-	150 - 250	1.00	150 - 250
Forklift	-	3	130 - 190	1.80	235 - 345
Reachstacker	-	3	200 - 260	1.80	360 - 470
SC	-	3+1	265 - 290	1.80	480 - 525
RTG	6	4+1	260 - 300	2.40	625 - 720
RTG	7	5+1	290 - 310	2.75	800 - 855
RTG	8	5+1	300 - 350	2.75	825 - 965
RMG	9	4+1	340 - 430	2.80	955 - 1205

Source: Montfort et al. (2012)

It is assumed that the transshipment ratio of the UK ports is below 10%. This threshold was suggested Notteboom (2010) and has been corroborated by a European Union study Pastori, (2015) on the modal share of freight transport at EU ports. According to this report, the port of Felixstowe had a transshipment ratio of 8.2% in 2012, while the port of Southampton reshipped just 5.5% of its throughput in the same year. Therefore, a value of transshipment of 10% has been adopted to calculate the STS-equivalent annual yard capacity. With a transshipment level of 10%, the transformation coefficient is CY T S = 1.0526. The STS-equivalent capacity of the UK deep-water container port system is shown in table 8.

Table 7. Storage yard capacity of the UK DWCP

	A_T $[m^2]$	A_Y $[m^2]$	Yard equipment	GS	H $[m]$	K_y $[TEU]$
Felixstowe	2,478,479	1,048,759	RTG(6, 4+1)	69,917	2.40	6,124,751
Southampton	954,056	602,125	SC (3+1)	40,142	1.80	2,637,306
London Gateway	425,506	391,536	RMG(10, 4+1) (ASC)	26,102	2.80	2,667,665

Table 8. Capacity of the UK DWCP (2017)

	K_{STS} [TEU]	K_y [TEU]	K_{max} [kTEU]	Throughput (2016) [kTEU]	Spare capacity [%]
Felixstowe	5,546,983	6,447,107	5,547	4,016	28
Southampton	2,389,132	2,776,112	2,389	2,037	15
London Gateway	1,721,103	2,808,069	1,721	1,497	13
UK DWCP	9,657,218	12,031,287	9,657	7,550	22

9. Conclusions

Firstly, a taxonomy of container ports and container terminals have been described, introducing the new concept of deep-water container terminal (DWCT).

Using this theoretic contribution, a method for the appraisal of the capacity of container terminals has been explained. The container terminal has been decomposed in four subsystems (ship-to shore, yard storage, receipt and deliver and horizontal transfer). It has been deemed by hypothesis that the receipt and delivery, and horizontal transfer subsystems do not introduce constraints to capacity. Two separate methods allow for the evaluation of the capacity of the ship-to-shore and the yard storage subsystems. The capacity model has established the maximum theoretical capacity of the UK deep- water container ports at 9.657 MTEU.

References

Agerschou, H., 2004. Planning and design of ports and marine terminals, 2nd ed. Thomas Telford Ltd., London.

Bichou, K., 2009. Port operations, planning and logistics. Informa Law from Routledge.

Charlier, R.H., 2013. Life cycle of ports. Int. J. Environ. Stud. 70, 594–602. https://doi.org/10.1080/00207233.2013.823049

Dally, H.K., 1983. Container Handling and Transport — A Manual of Current Practice. Cargo Systems IIR Publications Ltd, London.

Dharmalingam, K., 1987. Design of storage facilities for containers — a case study of Port Louis Harbour, Mauritius. Ports Harb. 27–31.

Drewry Shipping Consultants, 2018. Study findings warn of diminishing economies of scale from new generation of megaships [WWW Document]. URL https://www.drewry.co.uk/news/news/study-findings-warn-of-diminishing-economies-of-scale-from-new-generation-of-megaships (accessed 4.10.18).

Frankel, E.G., 1987. Port planning and development. Wiley, New York.
Haralambides, H.E., Cariou, P., Benacchio, M., Genova, Á., 2002. Costs , Benefits and Pricing of Dedicated Container Terminals. Int. J. Marit. Econ. 2002 21–34. https://doi.org/10.1057/palgrave/ijme/9100031
Hoffmann, P., 1985. Container facility planning: a case description, in: Port Management Textbook Containerization. Institute of Shipping Economics and Logistics, Bremen, pp. 353–364.
Itsuro, W., 2001. Container Terminal Planning — A Theoretical Approach.
JOC, 2017. Midsize vessels outpace mega-ships in berth productivity.
Kendall, D.G., 1953. Stochastic Processes Occurring in the Theory of Queues and their Analysis by the Method of the Imbedded Markov Chain. Ann. Math. Stat. 24, 338–354. https://doi.org/10.1214/aoms/1177728975
Kuo, T.C., Huang, W.C., Wu, S.C., Cheng, P.L., 2006. A case study of inter-arrival time distributions of container ships. J. Mar. Sci. Technol. 14, 155–164.
Lee, A.M., 1966. Applied queueing theory. MacMillan, London.
Ligteringen, H., Velsink, H., 2014. Ports and terminals, Second. ed. Delft Academic Press / VSSD, Delft, Netherlands.
Montfort, A., Aguilar, J., Vieria, P., Noemi, M., Obrer, R., Calduch, D., Martin, A.M., Sapina, R., 2012. Manual de capacidad portuaria: aplicación a terminales de contenedores. Valenciaport Fundation, Valencia.
Musso, A., Piccioni, C., Van de Voorde, E., 2013. Italian seaports' competition policies: Facts and figures. Transp. Policy 25, 198–209. https://doi.org/10.1016/j.tranpol.2012.11.001
Notteboom, T.E., 2010. Concentration and the formation of multi-port gateway regions in the European container port system: An update. J. Transp. Geogr. 18, 567–583. https://doi.org/10.1016/j.jtrangeo.2010.03.003
Notteboom, T.E., Cariou, P., 2009. Fuel surcharge practices of container shipping lines: is it about cost recovery or revenue-making?, in: Proceedings of the IAME2009 Conference, International Association of Maritime Economists, Copenhagen, June 24-26, 2009. Copenhagen.
Obrer-Marco, R., Aguilar, J., 2014. Modélisation continue de l'accostage des navires pour le calcul de la capacité des quais. Application aux grands terminaux à conteneurs espagnols. Rev. Paralia 7, 1–12. http://dx.doi.org/10.5150/revue-paralia.2014.n02
OECD, 2015. The impact of Mega-Ships. International Transport Forum.
Pastori, E., 2015. Modal share of freight transport to and from EU Ports. European Union, Strasbourg.
Puertos del Estado, 2011. ROM 2.0-11 Design and construction of Berthing & Mooring Structures. Madrid.
Rijsenbrij, J.., Wieschemann, A., 2011. Sustainable Container Terminals: A Design Approach, in: Böse, J.W. (Ed.), Handbook of Terminal Planning. Springer.
Robinson, R., 2002. Ports as elements in value-driven chain systems: the new paradigm. Marit. Policy Manag. 29, 241–255. https://doi.org/10.1080/03088830210132623
Rodríguez, F., 1977. Capacidad de los muelles. Ministerio de Obras Públicas y Transportes, Madrid.
Steenken, D., Voß, S., Stahlbock, R., 2004. Container terminal operation and operations research-a classification and literature review, in: OR Spectrum. pp. 3–49.
Suykens, F., Van De Voorde, E., 1998. A quarter a century of port management in Europe: objectives and tools. Marit. Policy Manag. 25, 251–261. https://doi.org/10.1080/03088839800000037
Thoresen, C.A., 2014. Port Designer's Handbook, 3rd Edition. ed. ICE Publishing, London.
UNCTAD, 1985. Port Development: A Handbook For Planners In Developing Countries, 2nd ed., rev. and expanded. ed. United Nations, New York. https://doi.org/10.1038/117262a0
Van de Voorde, E., Winkelmans, W., 2002. A general introduction to port competition and management, in: Port Competitiveness - An Economic and Legal Analysis of the Factors Determining the Competitiveness of Seaports. De Boeck Ltd, Antwerp, Belgium, pp. 1–16.
Van Hassel, E., Meersman, H., Van de Voorde, E., Vanelslander, T., 2016. Impact of scale increase of container ships on the generalised chain cost. Marit. Policy Manag. 43, 192–208. https://doi.org/10/gfdc5g
Veeke, H.P.M., Ottjes, J.A., Lodewijks, G., 2008. The Delft systems approach: analysis and design of industrial systems. Springer, London.
Verhoeff, J.M., 1981. Zeehavenconcurrentie: overheidsproduktie van havendiensten, in: Verhoeff, J.M. (Ed.), Vervoers- En Haveneconomie: Tussen Actie En Abstractie. Stenfert Kroese, Leiden, pp. 181–202.
Wilmsmeier, G., Monios, J., 2013. Counterbalancing peripherality and concentration: An analysis of the UK container port system. Marit. Policy Manag. 40, 116–132. https://doi.org/10.1080/03088839.2012.756588
World Bank, 2007. Port Reform Toolkit PPIAF. Washington. https://doi.org/10.1596/978-0-8213-6607-3
Wray, S., 2016. The Impact of the drive for the economies of scale on container terminals. WSP.