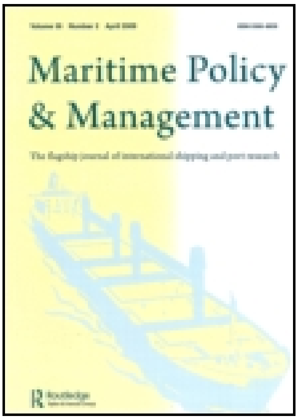

Maritime Policy & Management

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tmpm20

Reduction of emissions along the maritime intermodal container chain: operational models and policies

Christos Kontovas [a] & Harilaos N. Psaraftis [b]

[a] School of Naval Architecture and Marine Engineering, National Technical University of Athens, Athens, Greece

[b] Laboratory for Maritime Transport, School of Naval Architecture and Marine Engineering, Zografos, Greece

Available online: 06 Jul 2011

To cite this article: Christos Kontovas & Harilaos N. Psaraftis (2011): Reduction of emissions along the maritime intermodal container chain: operational models and policies, Maritime Policy & Management, 38:4, 451-469

To link to this article: http://dx.doi.org/10.1080/03088839.2011.588262

MARIT. POL. MGMT., JULY 2011,
VOL. 38, NO. 4, 451–469

Reduction of emissions along the maritime intermodal container chain: operational models and policies

CHRISTOS KONTOVAS*† and HARILAOS N. PSARAFTIS‡

†School of Naval Architecture and Marine Engineering, National Technical University of Athens, Athens, Greece
‡Laboratory for Maritime Transport, School of Naval Architecture and Marine Engineering, Zografos, Greece

Emissions from commercial shipping are currently the subject of intense scrutiny. Among the top fuel-consuming categories of ships and hence air polluters are container vessels. The main reason is their high service speed. Lately, speed reduction has become a very popular operational measure to reduce fuel consumption and can obviously be used to curb emissions. This paper examines such an operational scenario. Since time at sea increases with slow steaming, there is a parallel and strong interest to investigate possible ways to decrease time in port. One way to do so is to reduce port service time. Another possible way to minimize disruption and maximize efficiency is the prompt berthing of vessels upon arrival. To that effect, a related berthing policy is investigated as a measure to reduce waiting time. The objective of reducing emissions along the maritime intermodal container chain is investigated *vis-à-vis* reduction in operational costs and other service attributes. Some illustrative examples are presented.

1. Introduction

Air pollution from ships has been at the center stage of discussion by the world shipping community at least during the last decade. Looking at developments at the International Maritime Organization (IMO) level, thus far progress as regards air pollution from ships has been mixed and rather slow. On the positive side, in November 2008, the Marine Environment Protection Committee (MEPC) of the IMO unanimously adopted amendments to the MARPOL Annex VI regulations that deal with sulfur oxide (SO_x) and nitrogen oxide (NO_x) emissions. On the other hand, carbon dioxide (CO_2) is the most prevalent of Greenhouse Gases (GHGs) that are responsible for climate change, but there are currently no regulations regarding CO_2 emissions. Shipping has thus far escaped being included in the Kyoto global emissions reduction target for CO_2 and other GHGs. But it is clear that the time of non-regulation is rapidly approaching its end, and measures to curb future CO_2 growth are being sought with a high sense of urgency. At the IMO, two groups of measures are being currently discussed. The first relates to the so-called Energy Efficiency Design Index, an index that aims to assess a ship's energy efficiency. The second relates to market-based measures for GHGs. A full discussion of either set of measures is beyond the scope of this article, we note however that both relate to the ship and not to the overall supply chain.

*To whom correspondence should be addressed. E-mail: xkontovas@gmail.com

Maritime Policy & Management ISSN 0308–8839 print/ISSN 1464–5254 online
http://www.tandf.co.uk/journals
DOI: 10.1080/03088839.2011.588262

Since fuel costs and emissions are directly proportional to one another (both being directly proportional to the quantity fuel burned), it would appear that reducing both would be a straightforward way toward an environmental ''win–win'' solution. In an operational setting, one of the obvious tools for such a speed reduction: sail slower, and you reduce both emissions and your fuel bill. Slow steaming has been a strategy much employed in difficult trading conditions, where fuel prices have steeply increased and freight rates have remained low. Slow steaming may also be seen at present as an answer to over-capacity. The downside, especially in a fast liner trading operation, is that the shippers might object to longer voyage times and that to maintain the same throughput, it might be necessary to put extra ships on the route.

In parallel, and given that time at sea increases with slow steaming, there is an increased interest to investigate possible ways to decrease time in port. One possible way to minimize disruption and maximize efficiency is the prompt berthing of their vessels upon arrival. Traditional practices implement the First-Come-First-Served (FCFS) service policy. But there may also be different and sometimes contradicting policies such as giving priority to larger vessels (that are more profitable) or to smaller vessels that have shorter service time. Many customers have contracts with terminal operators that ensure them guaranteed berth-on-arrival service—that is, the actual berthing occurs within 2 h of arrival. A related strategy is a system in which a line could book a berthing time slot in advance and is guaranteed service in that slot (''booking by rendezvous''). By reducing speed and arriving at port in a given time window instead of arriving early and then having to wait to be served, a ship may avoid a substantial amount of emissions, and, simultaneously, reduce operational cost.

This paper examines the fuel cost and emissions reduction of some of these scenarios. The objective of reducing emissions along the intermodal container chain is investigated *vis-à-vis* reduction in operational costs and other service attributes. Some illustrative examples are presented.

The rest of this paper is structured in the following way: Section 2 reports on the relevant background and describes the basics on emission calculations; Section 3 investigates the effects of speed reduction; Section 4 examines the issue of port time in the quest to reduce emissions; Section 5 addresses possible ways to reduce service time of land-side operations regarding efficient container handling and transfer; Section 6 examines the benefits of alternative policies such as the ''booking by rendezvous''; and Section 7 addresses the conclusions.

2. Background and basic algebra

2.1. *Relevant literature*

For anybody who wants to survey the state-of-the-art in this area, we first note that even though the literature on the broad area of ship emissions is immense, it is mostly centered on aspects that concern issues such as ship design, technology, propulsion, fuels, combustion, and the impact of emissions on weather and climate.

The 59th session of IMO's Maritime Environment Protection Committee (MEPC 59, July 2009) alone had 65 submissions on ship emissions by IMO member states and observer organizations. MEPC 60 (March 2010) had 64 submissions and MEPC 61 (September–October 2010) had 59 submissions. We collected and reviewed a large number of such documents, by focusing on relations linking parameters such as engine type and horsepower to produced emissions of various exhaust gases, and to various other reported statistics (for instance, bunker consumption). Among the number of related IMO documents, perhaps the most seminal one from 2000 to mid-2008 was the 2000 IMO Study [1] in which an international consortium led by Marintek (Norway) delivered a report on GHG emissions from ships which included an estimation of the 1996 emissions inventory and the examination of emission reduction possibilities through technical, operational, and market-based approaches. In 2008, the report of Phase 1 on the updated IMO 2000 study on GHG emissions from ships was presented [2].

Furthermore, outside IMO documents, detailed methodologies for constructing fuel-based inventories of ship emissions have been published amongst others by Corbett and Köhler [3], Endresen *et al.* [4, 5], Eyring *et al.* [6] and in Psaraftis and Kontovas [7, 8]. All these documents include detailed methodologies on calculating emissions and provide the basic relations that will be used in our estimations.

In spite of this immense literature, to our knowledge, little has been published on the links between emissions and logistics. The IMO approach is, by definition, ship-centered, and no consideration to other components of the supply chain, such as ports for instance, or to the entire chain itself, is given. The situation at the other end of the spectrum is similar: very little or nothing in the maritime logistics literature deals with emissions, most papers dealing with traditional cost and service criteria.

2.2. *Fuel consumption*

Air emissions are proportional to the fuel consumption of the main and auxiliary engines (including boilers). Note that in this article, the reduction in fuel consumption and emissions is estimated. Fuel consumption of auxiliary engines does not depend much on the speed of the vessel and, therefore, has no effect when estimating fuel reductions due to slow steaming.

For most ships, the main characteristics such as service speed, total installed power, and total fuel consumption for the service speed in normal conditions are known and can be found in databases that provide the characteristics of vessels. Two such databases have been extensively used in the literature: the IHS Fairplay Register of Ships (previously known as Lloyds Register of Ships provided by the Lloyd's Register Fairplay) and the Lloyd's List Intelligence database (previously known as the Lloyd's Marine Intelligence Unit LMIU database).

In general, fuel oil consumption of each engine (main engines and auxiliaries) is based on installed power (P), load factors (L), and the time (t) that the engines are operated and on the Brake Specific Fuel Consumption (BSFC). It is given as follows:

$$\mathrm{FC}\ (t/\mathrm{day}) = \mathrm{BSFC}\ (\mathrm{g/kWh}) \times 10^{-6}\,\mathrm{t/g} \times L(\%) \times P(\mathrm{kW}) \times t \times 24\,\mathrm{h/day}$$

To start with, given the fact that the BSFC and the power (P) depend on the ship (and the installed engine), there exists no generic formula to estimate the fuel consumption versus ship speed curve. Nearly in all emission-related studies, a constant specific fuel consumption both for main engines and auxiliaries is assumed. For the main engine this is realistic only for very small speed reductions. MAN Diesel [9] presents an example of reduced fuel consumption at low-load operation for large container vessels with 12K98MC-C6 engine. Sailing at 23 knots, the ship uses 75% of Maximum Continuous Rating (MCR) and the engine has a specific fuel consumption of 165.1 g/kWh. At 18.5 knots—that is 30% of MCR—the specific fuel consumption increases to 174 g/kWh, which is a difference of 5.4%.

Given that fuel consumption FC is a function of the power provided by the main engine and of the BSFC and assuming that the BSFC is constant, then the fuel consumption becomes proportional to the total installed power. In most papers, a cubic relation has been used. However, according to ship design textbooks, or speeds greater than 20 knots, an exponent of 4 or greater has to be used [10]. This seems to be consistent with engine manufacturer data that propose a relationship in the power of 4.5 for large high-speed container vessels [11]. Notteboom and Cariou [12] used regression analysis on data extracted from the IHS Fairplay Database and estimated the relationship between speed and installed power for containerships. Thus, they arrived at an exponent of 3.311—which is almost cubic.

The cubic relationship between speed and installed power that is traditionally assumed by naval architects based on hydrodynamics laws is not necessarily valid for container vessels that normally run at service speeds above 20 knots. In the quest to investigate such a relationship, we performed a regression analysis of about 4000 container vessels built from 1999 on (provided by IHS Fairplay online Sea-Web database). Based on this regression, the installed power P needed to sail at a design speed V (after removing statistical outliers) is given by the following relation:

$$P = 0.00311\,V^{5.1465}(R^2 = 0.947)$$

Of course, the reader should be cautious in interpreting and using the above result (particularly as regards the exponent of the speed), as this refers to the entire fleet database and not to a specific ship. Note also that the total installed power in the database refers to 100% MCR and to the design speed with a clean hull but this is not always the case. Normally, design speed corresponds to somewhere between 75% and 85% of MCR. A ship with a fouled hull and in rough weather will be subject to extra resistance and will need more power to sail, thus a sea margin of 15% has to be taken into account.

Even though the above regression result cannot be used for a single ship, combined with engine manufacturers reports, it can perhaps support the conjecture that the exponent of the speed for containerships is higher than 3. Personal communication with container line personnel tends to confirm such a conjecture.

2.3. *Estimation of emissions*

To find the equivalent CO_2 emissions that are produced, the bunker consumption should be multiplied with an appropriate emissions factor (F_{CO_2}) since emissions are directly related to fuel consumption. The emissions factor for CO_2 depends on the type of fuel used. In the early literature, however, an empirical emission factor of 3.17 that was not fuel-dependant has been extensively used. Lately, in most reports separate emissions factors for Heavy Fuel Oil (HFO) and for Marine Diesel Oil (MDO) are being used. For example, the update of the IMO 2000 study [1, 2], which has been presented at MEPC 58, uses slightly lower coefficients, namely 3.082 for MDO and Marine Gas Oil (MGO) and 3.021 for HFOs.

In order to ensure harmonization of the emissions factor used by parties under the United Nations Framework Convention on Climate Change and the Kyoto Protocol, the Carbon to Carbon Dioxide (CO_2) conversion factors used by the IMO should correspond to the factors used by the Intergovernmental Panel on Climate Change (IPCC).

Table 1. Comparison of emission factors kg CO_2/kg fuel [1].

Fuel type	GHG-WG 1/3/1	IPCC 2006 guidelines Default	IPCC 2006 guidelines Lower	IPCC 2006 guidelines Upper	Revised 1996 guidelines
MDO/MGO	3.082	3.19	3.01	3.24	3.212
LSFOs	3.075	3.13	3.00	3.29	
High-sulfur fuel oils	3.021				

In general, fuel consumption for both main engines and auxiliaries should be estimated separately. The reason is that auxiliaries do not normally use the same type of oil as the main engines. However, in the case of large container vessels, main engines and auxiliaries use both HFO [2] and therefore the 3.13 value to ensure the harmonization with the 2006 IPCC Guidelines (Table 1) will be used [13].

3. Speed reduction as an operational measure

As mentioned earlier, the literature on the specific topic of this paper (link between emissions and maritime intermodal logistics) is relatively scant. Still, there are a number of papers that may be considered as relevant. For instance, Perakis and Papadakis [14] examined the issue of speed optimization in the context of fleet deployment. Andersson [15] considered the case of a container line where the speed for each ship reduced from 26 to 23 knots and one more ship was added to maintain the same throughput. Total costs per container were reduced by nearly 28%. Eefsen [16] considered the economic impact of speed reduction of containerships and included the inventory cost. Cerup-Simonsen [17] developed a simplified cost model to demonstrate how an existing ship could reduce its fuel consumption by a speed reduction in low and high markets to maximize profits. Corbett *et al.* [18] applied fundamental equations relating speed, energy consumption, and the total cost to evaluate the impact of speed reduction. They also explored the relationship between fuel price and the optimal speed. Notteboom and Vernimmen [19] examined bunker fuel costs, which is a considerable expense in liner shipping. Their paper assessed how shipping lines have adapted their liner service schedules to deal with increased bunker costs which include the examination of speed reduction scenarios. Last but not the least, Devanney [20] in a paper that investigated the effect of bunker prices on VLCC spot rates, examined the issue of optimal speed as a function of fuel price and spot rate (optimal defined as maximizing average daily profits for the ship owner).

The effect of speed reduction has been extensively investigated by the authors of this paper. Psaraftis and Kontovas [21] investigated the simple scenario where a fleet of N identical ships (N: integer), each of capacity (payload) W loads from a port A, travels to port B with a known speed, discharges at B and goes back to port A in ballast, with a known speed. The main result of the analysis was that total emissions would be always reduced by slowing down, even though more ships would be used. Psaraftis *et al.* [22] focused on the case where total trip time was kept constant. Furthermore, Psaraftis and Kontovas [23, 24] took a look at various tradeoffs that are at stake in the goal for greener shipping and may impact the cost-effectiveness of the logistical supply chain and presented models that can be used to evaluate these tradeoffs.

Our generic approach assumes a container vessel that departs from port A and arrives at port B. There is no need to know the number of ports that the vessel stops in between. The vessel has covered a total distance of L nm from A to B carrying a payload W with an average (or constant) speed of V_0 (in knots). Port B can be the same with port A—in that case we are talking about a roundtrip. We also assume that fuel consumptions are known.

3.1. *The impact of speed reduction on total trip time*

We will first investigate the impact of speed reduction on total time. The time that the vessel spends at sea depends only on speed while time at port depends on many factors, such as amount of cargo to be handled, loading and unloading speed, etc. For the time being, we assume that the time in port is known.

The times that the vessel spends at sea and in port are expressed as follows:

At sea: Total time at sea $T_0 = \frac{L}{24 \cdot V_0}$ (days)

In port: Total time in port t_0 (days).

Thus, the total time is the sum of these two.

Now suppose that the ship operator wants to investigate the scenario of speed reduction. This may be for cost-related reasons or for environmental reasons (to decrease CO_2 emissions), or for any other reason as described in Section 3.2. Reducing speed means that the ship will now sail at a new speed V which will be a fraction of the original speed ($V = aV_0$ where $0 < a < 1$) and, hence, there will be an increase of the total time at sea, $T = \frac{L}{24V} = \frac{T_0}{a}$.

It is obvious that if time in port remains the same (port time difference $t - t_0$ equals 0), there will be a need to add a number of additional vessels (possibly fractional) in order to maintain the same throughput per year. In theory, even if more ships are added in a specific route, it has been proven that this is beneficial for the operator (but only in terms of bunker costs alone) and for the environment (reduced emissions). Whether or not speed reduction is overall more profitable to the operator depends on the additional costs of deploying the extra vessels. Speed reduction will also entail increased in-transit inventory costs, to be borne by the charterer, and these are proportional to the value of the cargo. For an analysis of related scenarios, see Refs [22, 24].

On the other hand, if time in port could be reduced ($t < t_0$), and in fact if "t" is such that the total time, including time in port, remains the same ($T + t = T_0 + t_0$), then there will be no need to add extra ships.

It should be realized that reducing port time may not be possible, as this would depend on a variety of factors that may concern either the ship, or the port itself, or both. But if time in port can be reduced at all, it can be a crucial factor to reducing ship total emissions. To our knowledge, this has not been investigated much in the literature. An attempt to investigate such scenarios was done by Psaraftis *et al.* [22]. It should be noted that even if the total time cannot be kept constant, any reduction in port time leads to a decrease of fuel consumption and, thus, to CO_2 emissions. The issue of port time in the quest to reduce emissions will be analyzed into detail in Section 4 and ways to achieve this with optimization of land-side operations and berthing priority service policies in Sections 5 and 6, respectively.

3.2. *Effect on fuel consumption*

In the above scenario, the daily fuel consumption and the time in port are assumed known. Furthermore, the time that the ship spends at sea can be calculated given that distance and speed are known. Thus, the following are known:

At sea:
  Fuel consumption F_0 (tons per day)

$$\text{Total time at sea } T_0 = \frac{L}{24 \cdot V_0} \text{ (days)}$$

In port:
  Fuel consumption f (tons per day)
  Total time in port t_0 (days).

The total fuel consumption for this trip is $FC_0 = F_0 \cdot T_0 + f \cdot t_0$.

As discussed above, after speed reduction, the new speed V will be a fraction of the original speed ($V = aV_0$, where $0 < a < 1$) and hence there will be an increase of the time at sea,

$$T = \frac{L}{24V} = \frac{T_0}{a}.$$

Realistic values for the speed reduction factor "a" can be in the range 0.8–0.95, which imply a speed reduction in the range of 5–20%. In general, for such small speed reductions, the effect of speed change on fuel consumption is assumed cubic for the same ship. However, many vessels are reported to sail as low as half of the normal speed. In very low-load cases and in the case of container vessels (having a design speed of more than 20 knots), a more case-specific speed-to-power relationship has to be derived (Section 2.2).

Generally speaking, the fuel consumption at the reduced speed F can be approximated as follows:

$$\frac{F}{F_0} = \left(\frac{V}{V_0}\right)^n \text{ given that } F_0 = kV_0^n, \text{ where } k \text{ and } n \text{ are known constants.}$$

Reductions in fuel consumption, emissions, and bunker cost will be presented as a function of n. Note that as discussed in Section 2.2, for the case of container vessels, a value of n greater than 3 has to be used.

We can compute the difference in fuel consumption for the above scenario as follows:

At sea:

$$\begin{aligned}\Delta(\text{consumption at sea}) &= F \cdot T - F_0 \cdot T_0 = F \cdot \frac{L}{24 \cdot V} - F_0 \cdot \frac{L}{24 \cdot V_0} \\ &\overset{V=aV_0}{=} \frac{L}{24 \cdot V_0}\left(F \cdot \frac{1}{a} - F_0\right) \overset{\frac{F}{F_0}=\left(\frac{V}{V_0}\right)^n}{=} \frac{L}{24 \cdot V_0}\left(\left(\frac{V}{V_0}\right)^n F_0 \cdot \frac{1}{a} - F_0\right) \\ &= \frac{L}{24 \cdot V_0}\left(a^n F_0 \cdot \frac{1}{a} - F_0\right)\end{aligned}$$

In port:

$$\Delta(\text{consumption at port}) = f \cdot t - f \cdot t_0 = f \cdot (t - t_0).$$

Thus, the total fuel consumption decrease due to slow steaming is

$$\Delta(\text{Fuel consumption}) = \frac{L}{24 \cdot V_0} F_0\left(a^{n-1} - 1\right) + f \cdot (t - t_0). \tag{1}$$

Note that the first addend is negative since, by definition, parameter "a" lies between 0 and 1 and L, F_0 and V_0 are always positive.

In the case where time in port is constant, $t - t_0$ is equal to 0 and it decreases ($t < t_0$). This leads to a negative $t - t_{0.}$ Thus, according to (1), for both cases' speed reduction leads to a decrease in fuel consumption per trip.

3.3. *Effect on CO_2 emissions*

To find the equivalent CO_2 emissions reduction, the reduction in bunker consumption has to be multiplied with the appropriate emissions factor (F_{CO_2}) since emissions are directly related to fuel consumption. As discussed in Section 2.3, in this paper we use a factor of 3.13, see Ref. [13].

Thus, using Equation (1), the reduction in CO_2 emissions is:

$$\Delta(CO_2 \text{ emissions}) = F_{CO_2} \cdot \left[\frac{L}{24 \cdot V_0} F_0\left(a^{n-1} - 1\right) + f \cdot (t - t_0)\right] \tag{2}$$

Note that since the change in fuel consumption is always negative (Section 3.2), there is always a reduction in fuel emissions and in the case where time in port can be decreased, the reduction is greater than in the case where time in port is kept constant.

In addition, note that, in general, emissions at sea are much more than emissions in port. The exact numbers depend on the ship type and size. While in port, ships consume much fewer fuel than while sailing and the time that the vessels spend at sea is only a small portion of the total trip time for large trips.

3.4. *Effect on fuel costs*

The fuel cost reduction can be estimated by assuming that the price of the fuel used by the ship is known and equal to p (assumed constant during the year). Even though it is assumed a constant in our analysis, p is very much market-related, and, as such, may fluctuate widely in time, as historical experience has shown. For example, following the economic crisis of mid-2008, in June 2008, the average prices in the Port of Rotterdam for Low-Sulfur Fuel Oil (LSFO; LS 380) and MDO were 644.5 and 1126.0 USD/ton, respectively. Prices then collapsed and came to as low as 193.5 USD/ton (LSFO) and 420.0 (MDO) in December 2008. Since then, prices have been increasing. In January 2010, the average prices are 463.50 and 586 USD/ton for LSFO and MDO, respectively.

In any case, the assumption of a constant price causes no loss of generality, as an average price can be used. Also, as the ship will generally consume different kinds of fuels during the trip and in port assuming a unique fuel price is obviously a simplification. But this causes no loss of generality either, as an average price can be assumed for the general case.

Using Equation (1), the reduction in fuel is:

$$\Delta(\text{fuel costs}) = p \cdot \left[\frac{L}{24 \cdot V_0} F_0\left(a^{n-1} - 1\right) + f \cdot (t - t_0)\right]. \tag{3}$$

4. Container ports: time considerations

As discussed above, the issue of port time in the quest of emissions reduction is very important. First of all, fuel consumption is proportional to the amount of time that a vessel spends at sea and in port. Thus, any reduction in the time that a vessel spends in port yields a reduction in fuel consumption, emissions, and bunker costs. This is true even in the absence of other operational measures such as speed reduction. In addition, as we discussed before, measures to reduce time in port are, also, very desirable when implementing speed reduction measures and in extreme cases, this may help to keep constant total trip times.

It should be realized that reducing port time may not be possible, as this would depend on a variety of factors that may concern either the ship, or the port itself, or both. For example, in the case of ferries [22], especially those engaged in short sea shipping, reducing port time comes at no extra cost, as the time that ship stays idle in port can be easily reduced. We can easily implement this under the assumption that the speed reduction will only lead to a small increase in total time so that passengers will still prefer using a ferry instead of other transportation modes, which is a logical assumption. Furthermore, this is feasible since ferries engaged in domestic sails and short sea shipping tend to spend a lot of time idle waiting for the next scheduled trip. Plus, reduced speed can lead to reduced fuel costs whose savings can be passed on to the passenger in terms of reduced ticket prices.

On the other hand, container ports are more advance in structures and procedures than other ports and most operations are done in very efficient ways; thus, there is only a little room for improvement. But if time in port can be reduced at all, it can be a crucial factor to reduce ship total emissions. Note that reduction of port time is also desirable by port operators since it brings more money to the port by being able to serve more vessels. Thus, there is an extra incentive for reducing time in port.

4.1. *The container terminal and port time components*

Bichou [25] presents the major bottlenecks in a container port (Figure 1). Some of these are outside the scope of our study. For instance, once the ship has completed the loading/unloading procedures she is ready to depart. Transporting the unloaded containers to the yard and transhipping them to land-based vehicles are outside the scope of this paper since the time consumed in the above procedures is not included in the vessel's turnaround time.

A list of procedures, mainly based on [26] are used in order to identify areas and operations that are time consuming. There are four possible states for a vessel: arriving, berthing, loading and unloading and, finally, departing. When a vessel that carries cargo is approaching the port, she may berth immediately or wait for one of the reasons illustrated in the following figure, the most important of which is that the berth may not be available. After berthing, there are also several reasons that can prevent the immediate start of loading or unloading operations. One of them is related to the cargo-handling equipment, which may be allocated elsewhere.

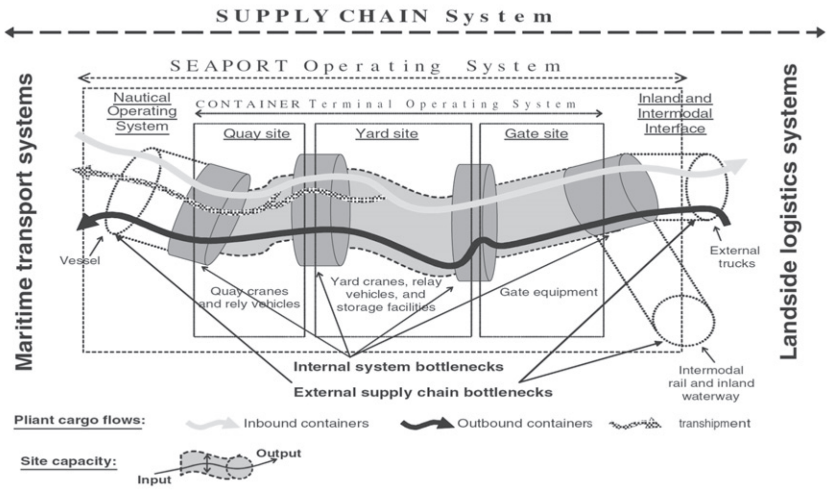

Figure 1. Illustration of bottleneck problems in a container port operating system [25].

In general, depending on the state of port congestion, the ship may or may not have to wait in an anchorage area outside the port, and the amount of total waiting time is t_w. After berthing, containers are unloaded/loaded from/onto the ship. Finally, when service is completed, the ship leaves the port. The amount of time that the vessels spend from berthing to departure is called service time (t_s).

Thus, in the scope of this paper the main time components are:

(1) waiting time before berthing (t_w)
(2) service time (t_s).

In the previous sections, time in port (t) was assumed to be an input. This is true in general since time in port is given in the schedules of liner companies. What is not known is what percentage of this time is used for waiting and servicing, respectively.

First of all, the waiting time as seen by the view of port planners and constructors is analyzed. Arrival rates for container ports which are used by more than one shipping lines conform to Poisson distribution [27]. Waiting time-to-service time ratios assuming $K=4$ and ∞ distributions for multi-user container terminal are presented in [27]. The ratios are empirical values resulting from economic feasibility studies and are in general lower than those for general cargo ports due to the value of time for container ships. For example, for more than four berths, the ratios for container terminals are 0.12 and 0.10 in the case of $K=4$ and $K=2\infty$ distributions, respectively. However, the assumption that is usually made for container terminals is that the time intervals between successive vessel arrivals do not follow the negative exponential distribution applicable to general cargo terminals, but rather follow an Erlang distribution, with $K=2$, because of the regularity of container ship arrivals. It is further assumed that vessel servicing time follows an $E2$ distribution as well [28]. Thoresen [29] assumes a ratio of the average waiting time or congestion time to the average berth service time of not higher than between 5% and 20%. Finally, using simulations, Dragović *et al.* [30] concluded that large container vessels spend at about 10% of their total time in port waiting to occupy a berth.

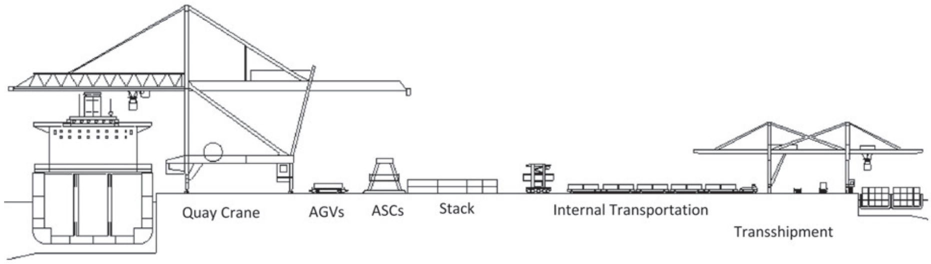

Figure 2. Process of unloading and loading a ship [33].

Thus, the biggest part of the time in port is the service time and mainly landside operations as we will discuss in the next section.

5. Container ports: reducing service time

The most feasible way to reduce time in port is through operational decisions regarding quayside operations (berth allocation, quay cranes scheduling, and vessel stowage). Cargo-handling equipment also plays an important role in the loading/unloading operation (Figure 2) itself. The most feasible way to reduce time in port is through operational decisions regarding quayside operations (berth allocation, quay cranes scheduling, and vessel stowage) [31, 32].

Container terminals in seaports constitute the interface between sea (container vessels) and land (trucks and trains) transportation of goods in the global supply chain. They do differ in size, function, and layout but, in principle, they all consist of the same sub-systems [34].

The four major areas of a seaport container terminal are:

Quay area for berthing container vessels
Transport area where internal transportation of containers takes place
Yard area where containers are transferred to and stored
Truck and train area for servicing the land-based vehicles.

This paper will briefly investigate three operational planning problems that deal with the utilization of the terminal resources, namely the quay space and the quay cranes. These problems are referred to as the *Berth Allocation Problem* (BAP), the *Quay Crane Assignment Problem* (QCAP), and the *Quay Crane Scheduling Problem* (QCSP). The berthing time and position at the quay for each vessel to be served within a given planning horizon are addressed in BAP problems, which will be discussed in Section 6. The quay crane related problems determine the set of cranes to serve each vessel (QCAP) and their work schedule (QCSP).

Optimizing terminal operations has received increasing interest over the past years. Vis and de Koster [33] review the relevant literature and illustrate the main logistics processes in a container terminal, whereas Steenken *et al.* [34] provide an overview of optimization methods terminal operations. The problem of allocating ships to berths (discrete case) or to quays (continuous case) is dealt among others in [35, 36]. The QCSP which refers to the allocation of cranes and to the scheduling of stevedoring operations can be solved with the use of dynamic programming as proposed in [37], or be addressed with a greedy randomized adaptive search procedure like the one analyzed in [38]. A branch and cut procedure for this class of problems is reported in [39] and the so-called "double cycling" procedures for loading and unloading are described [40]. Furthermore, yard operations such as storage policies and the design of re-marshalling are also of great importance. Lee *et al*. [41] address a yard storage allocation problem to reduce traffic congestion and [42] presents a model for container re-marshalling. For a review of the operation research literature of problems related to container terminal management, the reader may refer among others to Vis and de Koster [33] and Steenken *et al*. [34]. Another literature survey of this broad class of problems, with some 157 related references, is presented in Stahlblock and Voss [43]. Recently, Bierwirth and Meisel [44] present a survey of berth allocation and QCSPs in container terminals with particular focus on integrated solution approaches. Finally, following the trend of automation of seaport container terminals, several studies have investigated automation on container-handling systems. For more information, the reader is referred to Günther and Kim [45].

6. Container ports: reducing waiting time under an alternative service policy

This section deals with service policies that affect the waiting time before berthing. Port managers in container terminals attempt to reduce costs by efficiently utilizing port resources. Among all the resources, berths are the most important resources and good berth scheduling improves customers' satisfaction and increases port throughput, thus, leads to higher revenues. The usage of berths is scheduled by an intuitive trial-and-error method and varies from terminal to terminal.

Also, terminal operators usually have different priorities for different types of vessels. The priorities can be considered in BAP by converting them into cost coefficients of the penalty cost for vessels in the objective function. The most commonly used berthing priority policies are:

(1) FCFS
(2) Minimizing total completion time
(3) Maximization of total profit—Giving priority to bigger vessels
(4) Berthing closest to stack
(5) Priority service to big customers.

The traditional BAPs focus on the FCFS policy. In practice, this is the most commonly used policy for ports worldwide except for the case where ports have fixed assignments/berths to shipping lines. Another priority of the port manager may be to minimize total completion time. Allocating vessels to berths by simply minimizing the total time can lead to problems where vessels with smaller handling volume vessels (e.g., feeders) are receiving higher priorities than vessels with larger handling volumes which end up serviced at the end of the queues at each berth. Maximization of total profits can be achieved by giving priority to bigger vessels (that are more profitable than the smaller ones) or to smaller vessels (e.g., feeders) that have less service time and thus more ships are serviced in a given time. Other ports try to berth ships close to the storage location of the containers to be loaded.

In the recent scientific literature, very little has been written on the interface of BAP and emissions. Imai *et al*. [46] tried to modify the existing formulation of the

BAP in order to treat calling vessels at various service priorities, however, without relating this to minimization of port emissions. Recently, in [47], the discrete space and dynamic BSP where vessel arrival time is optimized to account for the minimization of port-related emissions, waiting time of vessels and delayed departures were studied. Alvarez *et al*. [48] present a hybrid simulation–optimization approach for evaluating berthing priority and speed optimization policies in a marine terminal and compare three berthing priority policies: FCFS, standardized estimated arrival time, and global Optimization of Speed Berth, and Equipment Allocations (GOSBEA).

Lately, many customers have contracts with the terminal operators that ensure them guaranteed Berth-On-Arrival (BOA) service— that is, the actual berthing occurs within two hours of arrival. In this case, the objective of berth scheduling is to minimize the penalty cost resulting from delays in the departures of those vessels and the additional handling costs resulting from non-optimal locations of vessels. Carriers usually inform the terminal operator on the Expected Arrival Time (ETA) and the requested departure time of vessels. Based on the information, the terminal operator tries to meet the requested departure time of all other vessels. However, when the arrival rate of vessels is high or when unexpected arrivals occur, it is not possible to complete services as pre-scheduled.

A related strategy is a policy in which a line could book a berthing time slot in advance and guaranteed service in that slot. In a seminal paper, Psaraftis [49] describes his experience from the real world when he was put in charge of the Piraeus Port Authority (PPA). The PPA was thinking of switching from the common policy of FCFS (first come, first served) to a system in which a line could book a berthing time slot in advance and to be guaranteed service in that slot. The original motivation was that this system would streamline utilization of cranes during peak periods and would effectively increase the capacity of the terminal. This scheme is referred to as "Booking by rendezvous".

The rationale for such a scheme can be understood by the fact that demand for a terminal's resources is by no means constant, as it is subject to the randomness of ship arrivals. To have adequate reserve capacity so as to meet peaks in demand without congestion, the terminal would have to invest into additional cargo-handling equipment, more piers, etc, which is a decision of strategic nature involving high investment costs. Before such a decision is contemplated, a natural consideration would be to see if the peaks in demand can be streamlined by an appropriate reallocation of traffic. Such a streamlining would reduce congestion and also reduce port costs due to overtime pay, among other things.

Streamlining the peaks in demand is the main objective of the "booking by rendezvous" system. The scheme is a way to minimize disruption, smoothen port demand peaks and maximize efficiency with the prompt berthing of vessels upon arrival. According to the scheme, a ship books service in advance, by declaring that the ship would arrive at the terminal at a prespecified date and time. If the ship is punctual in the rendezvous, the terminal guarantees berthing on arrival, bypassing other ships that have not booked, with a pre-arranged number of gantry cranes. If the ship misses the rendezvous, it is back in the queue together with all other ships.

In Piraeus, the system was implemented for the container terminal and the car terminal for the first time in 1999, and involved the allocation of one-third of both terminals to the scheme, and an advance notice of no less than 5 days before arrival (and in special cases 3 days). It is clear that the scheme was geared more to large mainline ships coming from distant destinations rather than smaller feeder ships, as the latter are unable to predict with accuracy their schedule 5 days in advance, as this depends on the situation in previous ports. There was high demand for the scheme by shipping companies, with request to extend it by lowering the required notice of 5 days, something that was not possible at the time. With the acquisition of 4 more gantry cranes, in 2002, the system was abolished, only to be introduced again in later years but not on a permanent basis. Other ports also have this scheme or variants of it.

Thus, given the "booking by rendezvous" the time in port is reduced by t_w. Therefore, the reduction in port time is: $\Delta t = t - t_0 = -t_w$ and the relative reduction in fuel consumption, costs, and emissions can be calculated as follows (Section 3).

In port (reductions by using the "Booking by rendezvous")

$$\Delta(\text{Fuel consumption}) = -f \cdot t_w \tag{4}$$

$$\Delta(\text{fuel costs}) = -p \cdot f \cdot t_w \tag{5}$$

$$\Delta(\text{CO}_2 \text{ emissions}) = -F_{\text{CO}_2} \cdot f \cdot t_w. \tag{6}$$

We shall now attempt to analyze the effect of this system as a way to help the implementation of speed reduction measures. Clearly, it would not make sense for a container vessel to speed to a port only to have to wait there because of congestion. If the ship can book by rendezvous, savings in fuel (and emissions) can be realized and congestion can be avoided at the same time.

Let us assume that a vessel is engaged in the container market. Assume also as before that after the implementation of speed reduction (time at sea increases), the time in port is reduced by t_w. Given that the reduction in port time is $t - t_0 = -t_w$, Equations (1)–(3) can be used to estimate the reduction in fuel consumption, fuel costs, and emissions as follows:

$$\Delta(\text{Fuel consumption}) = \frac{L}{24 \cdot V_0} F_0\left(a^{n-1} - 1\right) - f \cdot t_w \tag{7}$$

$$\Delta(\text{fuel costs}) = p \cdot \left[\frac{L}{24 \cdot V_0} F_0\left(a^{n-1} - 1\right) - f \cdot t_w\right] \tag{8}$$

$$\Delta(\text{CO}_2 \text{ emissions}) = F_{\text{CO}_2} \cdot \left[\frac{L}{24 \cdot V_0} F_0\left(a^{n-1} - 1\right) - f \cdot t_w\right]. \tag{9}$$

As one may notice, the first addend is negative since, by definition, parameter "a" lies between 0 and 1 and L, F_0, and V_0 are always positive thus there will always be a reduction in fuel consumption, bunker cost, and emissions. Finally, note that the liner company is benefited by this scheme since there is a reduction in fuel costs and the port increases port throughput, thus, leading to higher revenues. In this "win–win" scenario, the environment and society are also benefited from the reduction in CO_2 emissions.

6.1. *An example*

Our example is based on a real route, the North Europe–Asia route AE1 route served by the CKYH alliance (Figure 3). The AE1 route covers nine ports on the

Figure 3. CKYH Joint North Europe Express Service AE1.
Source: COSCO Line.

North Europe–Asia trade. Suppose that we want to investigate the following scenario: A vessel employed in the Far East–Europe trade, will decrease its speed in the Singapore–Rotterdam leg (that is the last Asian–first European port route).

We also assume that the maneuvering time and canal transit time (Suez) will be constant before and after the implementation of speed reduction. Note that in practice, this assumption may not always be correct as ships transiting Suez are grouped in convoys that transit the canal every several hours. The inputs are as follows:

Distance Singapore–Rotterdam: $L = 8353$ nm
Average speed: $V_0 = 23$ kn
Fuel consumption: at sea $F_0 = 150$ t/day and in port $f = 8.4$ t/day and
Time in port $t_0 = 1.93$ days.

For reasons of simplicity, we omit the detailed calculations and we illustrate the results in the following figures.

Figure 4 presents the percentage of reduction in fuel consumption and cost, and CO_2 emissions for the trip from Singapore to Rotterdam due to speed reduction. The calculations were performed using Equations (1)–(3). As discussed in Section 2.2, the power requirement P is proportional to the speed V to the power of n. In the above figure, the results are shown for $n = 3$ (cubic relation), $n = 4.5$ (according [11]) and $n = 5.15$ as proposed by the regression analysis that we performed.

As discussed in the previous sections, a speed reduction will lead to an increase in the time at sea but some scenarios can be implemented without the need to add more ships to maintain the same throughput. The scenario of not adding extra vessels is the case when the total turnaround time can be kept constant. Here, comes the role of the port in making this scenario feasible. Note also that in the above example, emissions at sea are almost 140 times more than those while in port.

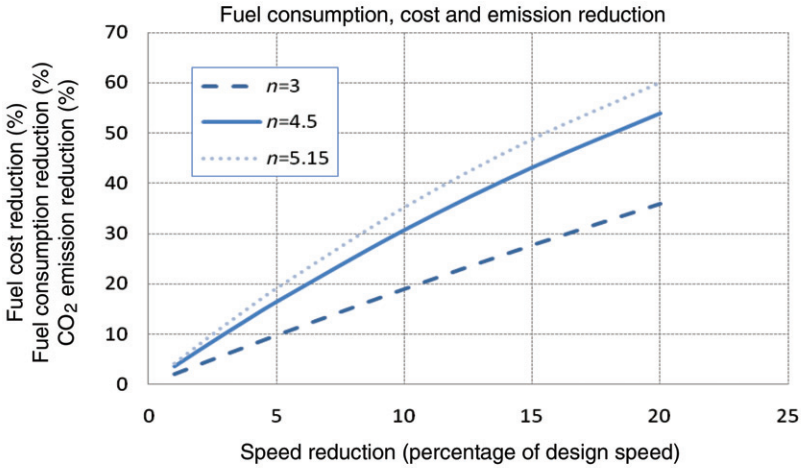

Figure 4. Reduction percentage due to speed reduction.

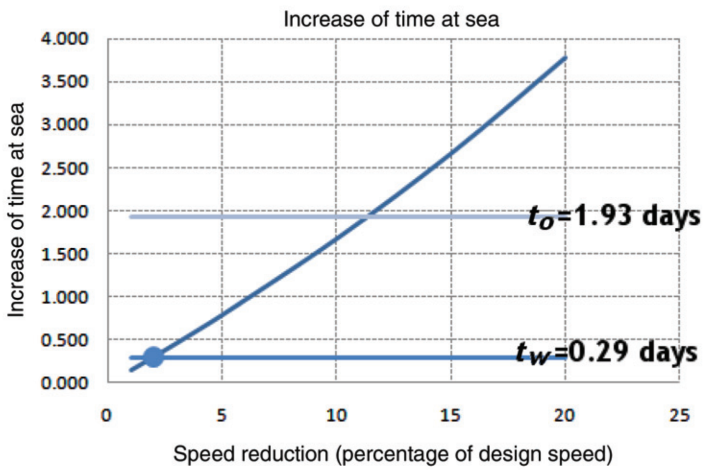

Figure 5. Time implications of speed reduction.

Without any reduction in the service time, imagine there is no congestion in the port of Rotterdam. This means that the vessel will berth as soon as it will arrive. This is the case with the ''booking by rendezvous'' system as discussed in the previous section (Figure 5).

The waiting and service times for each port vary. The time that a vessel spends in the Port of Rotterdam is 1.93 days and that this time includes the service and waiting times and not idle time [19]. According to Section 4.1, it is reasonable to assume a waiting time of 10–15% of the total port time, that is $t_w = 0.193$–0.29 days (or about 4.6 to 7 h). According to Section 4.4, it is reasonable to assume a waiting time of 10–15% of the total port time, that is $t_w = 0.193$–0.29 days (or about 4.6–7 h).

If the Port of Rotterdam uses the ''booking by rendezvous'' scheme, the amount of time that will be saved is capable of covering for the increased time due to a small speed reduction of just 2% for this leg. This 2% may not sound much, but the potential savings in absolute numbers can be significant: when fuel is (say) 600$/ton, a 2% reduction saves a total of more than 150 000 USD.

To sum up, the above example is clearly an oversimplification of the reality but it is evident that even small reductions in port time (such as the 2% discussed above) can lead to a small but still desirable emission and fuel cost reductions.

7. Conclusions

This paper has investigated an operational scenario, focusing on speed reduction, regarding container vessels and its effects on reducing emissions and fuel consumption were investigated. Further, the variation in specific fuel consumption due to change of engine load was considered and the relation between engine load and specific fuel consumption was assessed using regression analysis to identify a more appropriate relation between fuel consumption and vessel speed for container vessels.

It was seen that speed reduction under certain conditions is beneficial in terms of reducing emissions, but the real effectiveness of such a scheme depends on the possibility of reducing port time as well. Time in port can be reduced in parallel to the loss of time due to speed reduction. Port operations were analyzed in order to identify ways to reduce their operational time. Furthermore, a system that could reduce the waiting time in port before berthing was proposed (the "booking by rendezvous" system) and its implication on emissions was analyzed. Furthermore, even in the case where there is no waiting time, speed reduction can be beneficial for the shipper when bunker prices are high and market rates are low. Slow steaming may also be an answer to fleet over-capacity in the face of decreasing demand.

Acknowledgments

The research reported in this paper was funded in part by a gift from Det Norske Veritas (DNV) to the National Technical University of Athens.

References and notes

1. IMO, 2000, *Study of Greenhouse Gas Emissions from Ships. Study by Marintek, Econ Centre for Economic Analysis* (Pittsburgh, PA, USA: Carnegie Mellon University and DNV).
2. BUHAUG, Ø., CORBETT, J. J., ENDRESEN, Ø., EYRING, V., FABER, J., HANAYAMA, S., LEE, D. S., LEE, D., LINDSTAD, H., MARKOWSKA, A. Z., MJELDE, A., NELISSEN, D., NILSEN, J., PALSSON, C., WINEBRAKE, J. J., WU, W.-Q. and YOSHIDA, K., 2009, *Second IMO GHG Study 2009*, (London, UK: International Maritime Organization (IMO)).
3. CORBETT, J. J. and KÖHLER, H. W., 2003, Updated emissions from ocean shipping. *Journal of Geophysical Research*, **108**, 4650 pp.
4. ENDRESEN, Ø., SØRGARD, E., SUNDET, J., DALSØREN, S., ISAKSEN, I. S. A., BERGLEN, T. F. and GRAVIR, G., 2003, Emission from international sea transportation and environmental impact. *Journal of Geophysical Research*, **108**(D17), ACH 14-1—ACH 14-22, 4560.
5. ENDRESEN, Ø., SØRGARD, E., BEHRENS, H. L., BRETT, P. O. and ISAKSEN, I. S. A., 2007, A historical reconstruction of ships fuel consumption and emissions. *Journal of Geophysical Research*, **112**, D12301.
6. EYRING, V., KOHLER, H. W., VAN AARDENNE, J. and LAUER, A., 2005, Emissions from international shipping: 1. The last 50 years. *Journal of Geophysical Research*, **110**, D17306.
7. PSARAFTIS, H. N. and KONTOVAS, C. A., 2008, Ship Emissions Study. Report to Hellenic Chamber of Shipping, National Technical University of Athens, Greece, May. http://www.martrans.org/emis/emis.htm

8. Psaraftis, H. N. and Kontovas, C. A., 2009, CO_2 emissions statistics for the world commercial fleet. *WMU Journal of Maritime Affairs*, **8**(1), 1–25.
9. MAN Diesel, 2008, Low Container Ship Speed Facilitated by Versatile ME/ME-C Engines. MAN Diesel A/S Report, Copenhagen, Denmark, January.
10. Barrass, C. B., 2004, *Ship Design and Performance for Masters and Mates* (Oxford: Elsevier).
11. MAN Diesel, 2006, Ship Propulsion – Basic Principles of Ship Propulsion. MAN Diesel A/S Report, Copenhagen, Denmark, August.
12. Notteboom, T. and 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*, June 2009, Copenhagen.
13. Imo, 2008, Liaison with the Secretariats of UNFCCC and IPCC concerning the Carbon to CO_2 conversion Factor. MEPC 58/4/3.
14. Perakis, A. N. and Papadakis, N., 1987, Fleet deployment optimization models, part 1. *Maritime Policy and Management*, **14**(2), 127–144.
15. Andersson, L., 2008, Economies of Scale with Ultra Large Container Vessels. MBA assignment no 3, The Blue MBA, Copenhagen Business School.
16. Eefsen, T., 2008, Container Shipping: Speed, Carbon Emissions and Supply Chain. MBA assignment no 2, The Blue MBA, Copenhagen Business School.
17. Cerup-Simonsen, B., 2008, Effects of Energy Cost and Environmental Demands on Future Shipping Markets. MBA assignment no 3, The Blue MBA, Copenhagen Business School.
18. Corbett, J., Wang, H. and Winebrake, J., 2009, Impacts of speed reductions on vessel-based emissions for international shipping. In *Proceedings of Transportation Research Board Annual Meeting*, Washington, DC.
19. Notteboom, T. E. and Vernimmen, B., 2009, The effect of high fuel costs on liner service configuration in container shipping. *Journal of Transport Geography*, **17**, 325–337.
20. Devanney, J. W., 2010, The impact of bunker prices on VLCC spot rates. In *Proceedings of the 3rd International Symposium on Ship Operations, Management and Economics*, SNAME Greek Section, October 7–8, Athens, Greece.
21. Psaraftis, H. N. and Kontovas, C. A., 2009, Ship emissions: Logistics and other tradeoffs. In *Proceedings of the 10th International Marine Design Conference (IMDC 2009)*, Trondheim, Norway, May.
22. Psaraftis, H. N., Kontovas, C. A. and Kakalis, N., 2009, Speed reduction as an emissions reduction measure for fast ships. In *Proceedings of the 10th International Conference on Fast Transportation (FAST 2009)*, October 5–8, Athens, Greece.
23. Psaraftis, H. N. and Kontovas, C. A., 2009, Green maritime logistics: Cost-effectiveness of speed reductions and other emissions reduction measures. In *Proceedings of the International Symposium on Maritime Logistics and Supply Chain Systems 2009*, April 23–24, Singapore.
24. Psaraftis, H. N. and Kontovas, C. A., 2010, Balancing the economic and environmental performance of maritime transportation. *Transportation Research Part D*, **15**(8), 458–462.
25. Bichou, K., 2006, Review of performance approaches and a supply chain framework to port performance benchmarking. In *Port Governance and Port Performance*, edited by M. Brooks and K. Cullinane, Research in Transportation Economics, Vol. 17 (London: Elsevier), pp. 567–99.
26. Agerschou, H. (ed.), 1983, *Planning and Design of Ports and Marine Terminals* (London, UK: John Wiley).
27. Agerschou, H. (ed.), 2004, *Planning and Design of Ports and Marine Terminals* (London, UK: Thomas Telford Ltd).
28. Tsinker, G. P., 2004, *Port Engineering: Planning, Construction, Maintenance, and Security* (Hoboken, NJ: Wiley).
29. Thoresen, C., 2003, *Port Designer's Handbook* (London, UK: Thomas Telford Ltd).
30. Dragović, B., Park, N. K., Radmilović, Z. R. and Maraš, V., 2005, Simulation modeling of ship-berth link with priority service. *Maritime Economics and Logistics*, **7**(4), 316–335.

31. Notteboom, T. E., 2006, The time factor in liner shipping services. *Maritime Economics and Logistics*, **8**, 19–39.
32. Laine, J. T. and Vepsäläinen, A. P. J., 1994, Economies of speed in sea transportation. *International Journal of Phcal Distribution and Logistic Management*, **24**(8), 33–41.
33. Vis, I. and de Koster, R., 2003, Transshipment of containers at a container terminal: An overview. *European Journal of Operational Research*, **147**, 1–16.
34. Steenken, D., Voss, S. and Stahlbock, R., 2004, Container terminal operation and operations research – a classification and literature review. *OR Spectrum*, **26**, 3–49.
35. Cordeau, J., Gaudioso, M., Laporte, G. and Moccia, L., 2007, The service allocation problem at the Gioia Tauro maritime terminal. *European Journal of Operational Research*, **176**, 1167–1184.
36. Wang, F. and Lim, A., 2007, A stochastic beam search for the berth allocation problem. *Decision Support Systems*, **42**, 2186–2196.
37. Lim, A., Rodrigues, B., Xiao, F. and Zhu, Y., 2004, Crane scheduling with spatial constraints. *Naval Research Logistics*, **51**, 386–406.
38. Kim, K. H. and Park, Y. M., 2004, A crane scheduling method for port container terminal. *European Journal of Operational Research*, **156**, 752–768.
39. Moccia, L., Cordeau, J.-F., Gaudioso, M. and Laporte, G., 2006, A branch and cut algorithm for the quay crane scheduling problem in a container terminal. *Naval Research Logistics*, **53**, 45–59.
40. Goodchild, A. V. and Daganzo, C. F., 2006, Double cycling strategies for container ships and their effect on ship loading and unloading operation. *Transportation Science*, **40**, 473–483.
41. Lee, L., Chew, E., Tan, K. and Han, Y., 2006, An optimization model for storage yard management in transshipment hubs. *OR Spectrum*, **28**, 539–561.
42. Lee, Y. and Hsu, N.-Y., 2007, An optimization model for the container pre-marshalling problem. *Computers and Operations Research*, **34**, 3295–3313.
43. Stahlblock, R. and Voss, S., 2007, Vehicle routing problems and container terminal operations – An update of research. In *The Vehicle Routing Problem: Latest Advances and New Challenges*, edited by B. Golden, S. Raghavan and E. Wasil (New York: Springer Verlag).
44. Bierwirth, C. and Meisel, F., 2010, A survey of berth allocation and quay crane scheduling problems in container terminals. *European Journal of Operational Research*, **202**, 615–627.
45. Günther, H. O. and Kim, K. H., 2005, *Container Terminals and Automated Transport Systems* (New York: Springer Verlag).
46. Imai, A., Nishimura, E. and Papadimitriou, S., 2003, Berth allocation with service priority. *Transportation Research Part B*, **37**, 437–457.
47. Golias, M., Saharidis, G., Boile, M., Theofanis, S. and Ierapetritou, M., 2009, The berth allocation problem: Optimizing vessel arrival time. *Maritime Economics and Logistics*, **11**, 358–377.
48. Alvarez, J. F., Longva, T. and Engebrethsen, S., 2010, A methodology to assess vessel berthing and speed optimization policies. *Maritime Economics and Logistics*, **12**, 327–346.
49. Psaraftis, H. N., 1998, When a port calls . . . an operations researcher answers. *OR/MS Today*, **25**(2), 38–41.