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How do economies of density in container handling operations affect ships' time and emissions in port?

Evidence from Norwegian container terminals

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Abstract: Efficient port services are prerequisites for competitive and sustainable maritime transports. This paper makes advances in studying the determinants of the time that ships spend in port and the associated emissions to air. We estimate a production model for cargo handling based on a unique dataset containing each port of call at the largest container terminals in Norway in 2014. In turn, we use auxiliary engine emission factors to estimate particulate matter and nitrogen oxide emissions from ships at berth, to determine how the corresponding damage costs of air pollution vary with container throughput, location, and terminal investments. We find that Norwegian container terminals operate under increasing returns to density. Small ships that unload few containers are far from reaping economies of density, leading to high marginal time requirements for container handling and consequently high marginal external costs. From a Pigouvian taxation perspective, port charges should therefore be regressive in the number of containers handled. Moreover, we find that the external costs of maritime transports are severely understated when port operations are ignored. Our model allows determining the marginal productivities of port facilities. Thereby, it is instrumental in designing port charges that are diversified according to the quantity of containers handled and the service quality (i.e., the speed of handling operations). Regarding contextual factors, we find that establishing high-frequent liner services improves the ship working rate, while simultaneous calls at a terminal impede productivity. The type of container (import/export; empty/laden) also appears to influence the duration of ship working.

Keywords: *Air pollution; Ship working productivity; Marginal external costs; Translog function*; *Shipping emissions; Container ports*

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1. Introduction

Decision makers in Norway and Europe are determined to improve the economic and environmental performances of the transport system. Maritime transport receives attention by playing a pivotal role in international trade and thus in economic growth[1]. Moreover, intermodal transports are in general perceived as more environmental friendly than unimodal road transport, and to be instrumental in relieving road congestion. Norwegian and European freight transport policies therefore aim to strengthen the competitiveness of maritime and rail transports. In their 2011 white paper entitled *Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system*, the European Union (EU) lists 10 key objectives to achieve a competitive and resource efficient transport system. Among them is the target that 30% of road freight over 300 kilometers should shift to other modes such as maritime and rail transports by 2030, and more than 50% by 2050.

The Norwegian transport agencies' latest freight analysis[2] supporting the National Transport Plan concluded that the competition among modes in Norway is limited. While maritime transport specializes in long-haul of bulk commodities and consumer goods, more than 90 percent of the cargo transported by road relates to construction and consumer goods that require only short-distance distribution. For maritime transport, the greatest potential for a mode shift lies in replacing long-haul road transport by container shipping at sea. Consequently, our study emphasizes container handling.

Ports constitute an essential component of the maritime transport chain. Carriers' operating costs are associated with the distance travelled and the time it takes to complete the voyage (Cullinane and Khanna, 2000); the latter being affected by the time spent in ports, loading and unloading cargo. Ultimately, carriers trade economies of ship size for additional time costs in ports (Jansson and Schneerson, 1987). Hence, studies such as Tongzon (2009) find port efficiency (also comprising the speed of cargo handling operations) to be among the determinants of carriers' and shippers' port choices.

Containerships are among the largest and fastest growing maritime emitters (Corbett et al., 2009). The time that these ships spend in port are crucial for the environmental

[1] In the EU, 74 percent of all goods (measured by weight) entering and leaving Europe go by sea. In Norway, which is integrated in the European Single Market by being member of the European Economic Area agreement, maritime transport is the dominating mode for overseas freight transport.
[2] See *The Norwegian National Transport Plan* http://www.ntp.dep.no/Nasjonale+transportplaner/2018-2029/Godsprosjektet (Presentation, Summary and Freight Analysis are available in English).

impacts of maritime transport as their emissions whilst berthed can be the dominant source of urban air pollution (Cofala et al., 2007). This is especially relevant for Norway, where several of the largest ports are located in city centers. Schøyen and Bråthen (2015) find that containerships deployed in trade between Norway and continental European hub ports may spend 40-53% of their time in ports. While in port, most ships run auxiliary diesel engines to provide electricity for heating, refrigeration, cooling, lighting, and equipment, accompanied by air pollution. We emphasize nitrogen oxides (NO_x) and Particulate Matter (PM_{10}) because of their high damage potential in port cities.

Our paper makes advances in studying the determinants of container handling operations' durations, and thereby of emissions to air from ships during cargo handling and their associated external costs. A key contribution is its acknowledgement of the role that returns to density in handling operations – defined as the extended duration of loading/unloading operations[3] when an additional container is being handled, using the terminals' current infrastructures and facilities – play for ships' time and emissions in port: While previous studies on port emissions – including Tzannatos (2010), Berechman and Tseng (2012), and McArthur and Osland (2013) – have developed ship emission inventories and evaluated the external costs of emissions to air, we are unaware of other studies that relate in-port emissions to returns to density in handling operations. Moreover, little research has been devoted to external costs caused by feeders, which are the main concern of this paper. Feeders is the smallest category of container ships, and are mainly used in short-sea shipping and in draught-restricted ports (Stopford, 2009).

Our paper also makes advances in the study of determinants of ships' time spent in port by combining features of three strands of port studies: First, while previous *productivity and efficiency analyses* usually are based on annual (aggregate) data, we analyze each port of call to identify how the number of containers to be loaded/unloaded impact on the terminals' ship working rates; i.e., the ratio of containers handled to the duration of the cargo handling. This enables examining how well the terminals' current capacities are tailored to their demand, and to determine the marginal productivities of infrastructures and facilities. We are unaware of previous studies on this topic. Second, we map and operationalize relevant contextual variables based on insights from the *operations research* literature. Third, while our paper has similarities to previous *statistical analyses of ship turnaround times* and quay crane performances, it provides a richer description of

[3] "The duration of loading operations is the time between the start and finish of the ship working.

potential determinants of the duration of cargo handling operations than past studies, ranging from terminal inputs, throughput volumes, and ships' capacities and capacity utilizations to contextual factors such as temperature, wind force, and daylight.

Having identified key determinants of the durations of cargo handling operations, we use emission factors based on the U.S. Environmental Protection Agency's (EPA, 2009) methodology to identify how emissions to air and their corresponding damage costs vary with the throughput volume and terminal characteristics. Consequently, our results provide guidance for port pricing, allowing the identification of Pigouvian tariffs on cargoes and service quality premiums.

This paper is structured as follows. The next section reviews the current literature on the time factor in ports' cargo handling. Section 3 presents our empirical production model while section 4 provides a description of container port operations and identifies potential determinants of ship working productivities. Section 5 characterizes Norwegian container terminals and outlines the dataset, while section 6 presents the empirical results on air pollution damage costs. Section 7 concludes.

2. Literature review

This section briefly outlines how the time factor in cargo handling has been treated within three branches of the port literature, i.e., productivity and efficiency analysis, operations research, and statistical analysis of vessel port time.

2.1 Productivity and efficiency analysis

As noted by Ducruet et al. (2014), despite the diversity in approaches used to measure port productivity and efficiency, the time factor has largely been ignored. Production analyses of ports are abundant[4], but only a few papers take ship working rates into account (i.e., Suárez-Alemán et al., 2014; Tongzon, 2001). Talley and Ng (2016) criticize the established port productivity and efficiency literature for ignoring that ports produce service outputs as opposed to physical throughputs, and consider among others the ship working rate as an important measure of service quality. Martin et al. (2015) note that productivity and

[4] See for example Rødseth, K.L., Wangsness, P.B., 2015. Application of production analysis in port economics: A critical review of modeling strategies and data management, *TØI-rapport 1390/2015*. Transportøkonomisk institutt, Oslo. for a recent review (report in English).

efficiency studies generally ignore the impact of ship size on container terminals' workload and operations. Our paper adds to the literature on port production analysis by emphasizing port of calls as opposed to total throughputs at a port or terminal, by acknowledging the time factor in cargo handling, and by accounting for ship size and a wide range of other contextual factors that potentially impact ports' ship working productivities.

2.2 Operations research

The literature on operations research has become an important knowledge base for operations management for container terminals in recent years (Bierwirth and Meisel, 2010). This approach views loading/unloading operations as made up of a series of sub-processes that must be appropriately coordinated to avoid time-consuming bottlenecks (Kozan, 2000). Kozanoğlu (1983) combine simulation with cost minimization analysis to determine the optimal investment strategy for the port of Istanbul, emphasizing both investment costs and ships' waiting time costs. Similarly, Kozan (1994) combines capital budgeting techniques and queuing simulation in a cost-benefit analysis approach that determines the optimal balance between ships' waiting time costs and port infrastructure costs. Kozan (2000) studies the minimization of the time required to handle containers, and discusses how his approach can be imbedded in cost-benefit analysis[5]. This paper includes a sensitivity analysis on how changing the numbers of quay cranes, handling and transport equipment (i.e., reach stackers), and yard stacking equipment impact on the ship working time and associated air pollution damage costs.

2.3 Statistical analysis of vessel turnaround time

A third strand of literature undertakes statistical analysis of the time that ships spend in ports. The pioneering study in this area is by Heaver and Studer (1972). They analyze the loading of 1305 grain ships in Vancouver, focusing on how ship size, cargo type, and the number of berths visited impact the loading time and rate. This paper was followed by Edmond and Maggs (1976) who compile and analyze data on 1500 calls in UK's largest container terminals. They conclude that the turnaround times of ships vary substantially,

[5] Goss, R.O., 1967. Towards an economic appraisal of port investments. *Journal of Transport Economics and Policy* 1(3), 249-272. discusses the appraisal of port investments. His paper is motivated by a discussion on how port investments foster benefits for the users of the ports.

and that there are no simple linear relationships between the length of the ship's stay and either the size of the ship or the cargo handled. They argue that cooperation among agents involved in cargo handling and tide restrictions can be important factors for explaining the variation. Robinson (1978) focuses on the sizes of vessels and their turnaround times in Hong Kong, taking into account the berthing systems used. Tabernacle (1995) points out that the dependent variable used in the preceding studies – i.e., ship turnaround time – suffers from the disadvantage of containing factors that do not relate to port performance, e.g., tides, weather, and itinerary dictated sailing times. Tabernacle therefore focuses on crane productivity (i.e., moves or lifts per hour). A recent correlation analysis of ship turnaround times is presented in Loke et al. (2014). Our study provides a richer description of potential determinants of the duration of cargo handling operations than the studies reviewed in this section.

2.4 Analyzing ship working productivity

de Langen et al. (2007) note that while ship turnaround time has been discussed in the academic literature for decades, publicly available data and therefore empirical analyses are scarce. Ducruet et al. (2014) made a first attempt to examine time efficiency in world container ports. While their paper focuses on the average time a vessel stays in each port, our study features a unique dataset comprising each call at the largest container terminals in Norway in 2014. A distinct feature of our paper is its delimitation to analyzing the duration of ship working rather than ship turnaround times, allowing us to emphasize the terminals' cargo handling productivities and moreover to ignore idle time that is not related to cargo handling productivity.

3. Method

We develop a microeconomic production model framework for analyzing ports' container handling, as this is a standard tool for evaluating productivity and returns to density. Let $b \in \Re_+$ denote the duration of a loading/unloading operation, $y \in \Re_+$ denote the number of containers being loaded/unloaded, while $x \in \Re_+^N$ is a vector of port resources (e.g., the number of quay cranes and reach stackers). Moreover, let $z \in \Re_+^M$ be a vector containing factors that are not under the jurisdiction of the port, but which may influence its ship

working rate. The cargo handling operation can thus be formally summarized by a technology set:

$$T(z)=\left\{(x,b,y):(x,b)\text{ can produce } y \text{ for given } z\right\} \quad (1)$$

The model is assumed to conform to the usual axioms of production analysis. We refer to Färe and Primont (1995) for details. We emphasize the axioms of free disposability of inputs and outputs, which translate into monotonicity restrictions on the model. Particularly, the model framework views *b* as an input to loading/unloading operations, which by standard regularity conditions means that i) the minimal time required to load/unload cargo increases in the number of containers handled and ii) port resources serve as substitutes to handling time. For example, investing in an additional reach stacker can save time by preventing bottlenecks in container transport and stacking operations.

For empirical analysis of these technological relationships, we need to assign a function representation to the technology that can be estimated from data. We consider the time minimization function:

$$f(x,y;z)=\min_{b}\left\{b:(x,b,y)\in T(z)\right\} \quad (2)$$

Assuming that contextual factors change production possibilities in an (input-output) neutral way, we define the empirical counterpart to Eq. 2 as:

$$b=f(x,y)e^{g(z)+\varepsilon} \quad (3)$$

where ε is an error term that accounts for random noise and has a zero mean[6]. Taking logs, we derive the model to be fitted using ordinary least squares:

[6] The model specification in Eq. 3 is a common specification in the literature on Stochastic Frontier Analysis (SFA) and Stochastic Nonparametric Envelopement of Data (StoNED). These are frontier models with composed error terms used for benchmarking. If we used frontier models, the data would have to be aggregated to the ship or port level to compare the performances of actual decision making

$$\ln b = \ln f(x,y) + g(z) + \varepsilon \quad (4)$$

We assume that $g(z)$ is a linear regression model, while $\ln f(x,y)$ is (almost) Translog. When there are *i= 1,…,I* observations in the dataset, the Translog functional form can formally be written as:

$$\begin{aligned} \ln f(x,y) = \beta_0 + \sum_{n=1}^{N} \beta_n \ln x_{ni} + \beta_y \ln y_i \\ +0.5 \sum_{n=1}^{N} \sum_{n'=1}^{N} \beta_{nn'} (\ln x_{ni})(\ln x_{n'i}) + 0.5 \beta_{yy} \ln y_i^2 \\ + \sum_{n=1}^{N} \beta_{ny} (\ln x_{ni})(\ln y_i) \end{aligned} \quad (5)$$

where $\beta_{nn'} = \beta_{n'n}$. The Translog model is a well-established workhorse for evaluating "time elasticities" (i.e., cost elasticities) and returns to scale and density; see e.g. Wheat and Smith (2015).

Having outlined the methodology, we go on to examine the characteristics of the different stages of container handling. This exercise allows us to identify important explanatory variables to be included in the applied production analysis.

4. Container handling operations

Excellent characterizations of container handling operations are provided in Vis and de Koster (2003), Murty et al. (2005), and Günter and Kim (2006). Herein, we synthesize relevant aspects of these studies to identify potential determinants of the duration of loading/unloading operations. In turn, they will be operationalized and included in the preceding empirical analysis, as described in the Section 5.

units. Unfortunately, this reduces the sample size. Our study focuses on the properties of the time minimization function, characterized by its parameters, and we therefore prefer employing the mean-value estimator to data on individual port of calls.

The operations research literature views the terminal as consisting of several sub-systems and their dedicated assignments. Broadly, these systems are the *quay*, the *yard*, and the *gate*. Since containers are temporarily stored before/after accessing the terminal gate, we emphasize activities at the quay and the yard in this paper. We focus on three specific stages of container handling operations:

i. Loading/unloading of ships
ii. Transport of containers between the quay and the stack
iii. Stacking of containers

4.1 Loading/unloading of ships

This paper focuses on container terminals where quay cranes are used to load/unload vessels. The operational research literature analyzes how quay cranes should be scheduled to minimize the ships' waiting time; see Bierwirth og Meisel (2010) for an overview. In Norway, most container terminals are small, and visiting ships are correspondingly small and are the feeder type (Schøyen and Odeck, 2017). This means that usually only one quay crane is employed per ship. In the empirical analysis, we make a distinction between terminals that are equipped with only one quay crane and those that may be able to simultaneously use two cranes whilst loading/unloading a ship.

Vis and de Koster (2003) note that there is a distinction between the management of loading and unloading operations. While the unloading plan indicates the containers to be unloaded and where they are stowed in the ship, the crane driver exercises discretion in determining the order in which they are unloaded. The duration of the unloading operation depends upon the containers' location in the ship. When loading containers, there is hardly any flexibility. A stowage plan is made at the operational level, taking into account the ship's capacity and the supply and demand of containers in the terminals visited by the ship on its roundtrip.

In the empirical analysis, we control for the impacts of ship size and the ships' net carriage of containers the past week on the ship working time. This allows us to consider the impacts of ship capacity and capacity utilization, and implicitly how activities in other ports influence the productivity of the port under consideration. Moreover, we control for differences in the durations of loading and unloading operations.

4.2 Transport of containers between the quay and the stack

In Norway, it is common to use reach stackers to transport containers between the quay and the stack. Straddle carriers are available in the port of Oslo. Container terminals do have aprons adjacent to the quay/berth and/or in front of the yard area, among others serving as a buffer storage of containers between the ship and terminals stacking & storage area (Thoresen, 2014).

We consider the number of handling equipment available to be an important determinant of the ship working rate. If for example the terminal's capacity to transport containers between the quay and the stack is inferior to the capabilities of its quay cranes, the transport to the stack may become a bottleneck, hampering efficient loading/unloading. Moreover, different types of equipment such as reach stackers and straddle carriers have different working capacities.

Vis and de Koster (2003) note that ship working rates can be improved by appropriate berth allocation, minimizing the distance from the quay to the stack. Moreover, the routing of vehicles is important to minimize empty-travel by combining loading and unloading jobs. We do not have access to information about the distance between the berth and the stack for each call, as well as the routing of vehicles. Instead, we control for the sizes of the terminal areas, which of course are crude indicators of the distance travelled.

Günter and Kim (2006) note that container terminals usually have dedicated areas for reefer, containers carrying dangerous goods, empty containers, and non-standardized containers. The locations of these holding areas influence the distance travelled to/from the quay. Thus, it makes sense to control for how the time to load/unload these container types differ from "standard containers". Unfortunately, the available data only allow distinguishing empty from laden containers.

4.3 Stacking of containers

Containers are temporarily stored in stacks after arriving in the port. In Norway, reach stackers are commonly used for stacking. In addition, the port of Oslo uses Rubber Tyred Gantry (RTG) cranes that ensure denser stacks.

While stacking is useful for saving space, it can also hamper the terminals' ship working rates by requiring reshuffling of stacks to retrieve containers. Vis and de Koster (2003) indicate the necessity to improve other aspects of container handling to circumvent the

time loss associated with high stacks. One measure that can prevent delays is for the port to prepare for incoming calls, e.g., by retrieving containers to be loaded prior to the ship's arrival and interim storing of containers near the quay.

Unfortunately, we do not have access to information about stacking and the ports' preparations for loading/unloading operations. However, our dataset allows identifying the total number of containers handled by the port in a given period, which serves as a proxy for the capacity utilization of the port and thus the requirement to establish high stacks.

4.4 Other determinants

Meteorological conditions can play an important role in determining the cargo handling productivity. Murty et al (2005) state that the expected driving time of a transport vehicle changes from season to season and across rainy and non-rainy days. In Norway, there is snow and ice during the winter, which make driving conditions difficult. Also, high wind hinders the use of quay cranes, partly because they are subject to a maximum wind force regulation. Visibility is also likely to influence the speed of handling operations. Thus, we consider daylight to be a potential determinant of ship working productivity.

Some ships are observed to frequently visit one or a few ports in Norway. We hypothesize that the ship working rate improves when ships visit frequently, due to the learning effect and better communication between the ship's and the port's crews. A similar argument can be found in Tabernacle (1995).

5. Dataset and variable specification

Norway is among the countries with the longest coastlines. Yet, it is a small, sparsely populated country. The Norwegian port system is therefore unusual in the sense that its plentiful ports are small and scattered. The small- and medium-sized container ports considered in this study are gateway ports, in contrast to the large hub-ports that dominate the port productivity and efficiency analysis literature.

Figure 1: *Map of southern Norway (Red dots refer to the ports in the sample)*

Dry and wet bulks are the dominating cargo types in the Norwegian port sector. According to Statistics Norway, containerized cargo amounted to 3.37 percent (1.5 million tons) of the total tonnage handled by Norwegian ports in the last quarter of 2016. However, as previously mentioned, competitive container transport by sea is viewed as one of the most promising measures to achieve a mode switch from road to maritime freight transport. Container port productivity is consequently on the agenda of Norwegian bureaucrats and policy makers. Container shipping also receives attention because it is more land-intensive than bulk cargoes.

The dataset used in this study contains information about *each call* where containers (but no other cargo types) were loaded/unloaded within the largest container ports in Norway. These are the ports of Moss, Borg, Oslo (comprising Sjursøya and Ormsund[7] container terminals), Drammen, Kristiansand, Stavanger, Larvik, and Ålesund in 2014. Ships that call on either Ormsund or Sjursøya *only* are assigned to the terminal in question, while ships that call on *both* terminals (e.g., unloads in Sjursøya and loads in Ormsund whilst in Oslo) are omitted. This leads to the exclusion of 113 observations. This step is taken to ensure that all observations are comparable, i.e., take place at one terminal only, and because of the ambiguity in how to specify port inputs for "greater Oslo"[8]. In total, the dataset is made up of calls at nine different locations.

[7] In 2015, the Ormsund container terminal closed and the Sjursøya terminal was further developed to absorb containers from Ormsund.

[8] Preliminary analysis shows that aggregating Sjursøya's and Ormsund's port inventories into Oslo's aggregate inventory results in observations with access to substantially more inputs than observations at the other seven ports. In turn, the fitted time minimization function is increasing in the cargo handling

The applied variables from our dataset are described and summarized in Table 1. Our dataset combines information from several data sources: First, information about the loading and unloading of containers was collected from Statistics Norway's port statistics[9]. This is the source for the variables *Duration, Containers, Spring, Summer, Autumn, Gross tonnage, Ship throughput, Frequency, Port Activity, Loading, Empty* and *Simultaneous calls.* Second, a terminal inventory (comprising the variables *Area*, *Quay cranes, Transport and stacking equipment)* was provided by Halvor Schøyen, who compiled it whilst undertaking the research documented in Schøyen and Odeck (2013, 2017). Supplementary information about the inventories of Sjursøya and Ormsund container terminals was provided by Oslo's port authority upon request. Third, information about meteorological conditions whilst loading/unloading was collected from the Norwegian Meteorological Institute's historical weather database entitled eKLIMA. This is the source of the variables *Ice* and *Gale*. The variable *Daylight* is calculated using the U.S. National Oceanic and Atmospheric Administration's sunrise/sunset calculator.[10] In total, 2345 calls are contained in the dataset. However, some of these calls concern 8-foot containers relating to the oil industry (612 observations), bulk carriers (43 observations), and Ro-ro containers (14 observations) that were omitted prior to estimation. Moreover, 14 observations were deleted because they reported i) more than 60 containers loaded/unloaded per hour and/or ii) more than 1000 containers per call and/or iii) more than 80 hours of berthing. The container per hour cut-off was selected based on a priori knowledge that the Norwegian container terminals consider 30 containers loaded/unloaded per hour as a highly efficient quay crane operation. If a port uses two cranes simultaneously, which is the realistic maximum for the case under consideration, the cut-off is at 60. The other cut-offs were selected based on a scatterplot of the duration of berthing and the number of containers loaded/unloaded, to avoid data points that are located far from other data points. Implementing these selection criteria along with omitting ships that simultaneously call on Sjursøya and Ormsund reduce the sample size to 1,549 calls. When contextual variables are included, the sample is reduced to 1501 observations because *Daylight* could not be estimated for all observations.

We assume that the time minimization function comprises the number of containers loaded/unloaded and the terminal inventory. In Schøyen's dataset, the latter encompasses

equipment at all data points (i.e., investing in equipment increases the duration of the cargo handling), which we consider an unreasonable result.

[9] This data has been made available subject to a confidentiality clause.

[10] See https://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html

i) port area (sq.km), ii) berth length (m), iii) quay cranes (nr), iv) yard cranes (nr), v) straddle carriers (nr), and vi) cargo handling trucks (nr). The latter comprises reach stackers, frontlift handlers, and toplifters. Because these variables do not vary within terminals, there is too little variation to include all of them in a full-blown Translog specification. Moreover, the variables are highly correlated, which represents a multicollinearity problem. To resolve these issues, we simplify the specification i) by modeling the access to quay cranes by a dummy variable that takes the value 1 if the terminal has access to employing more than 1 crane when loading/unloading a ship and 0 if the terminal has only one quay crane, and ii) by maintaining reach stackers, frontlift handlers, and toplifters in an aggregate input (i.e., Handling equipment). This procedure ensures that there are no zeros in the transport and stacking equipment data, which allows taking logs. A similar route is followed by Cullinane et al. (2002).

We emphasize that the aggregated equipment should be of similar quality and working capacities, and do therefore not include straddle carriers and RTG yard cranes in the Handling equipment variable. In Norway, straddle carriers and RTG yard cranes can only be found in the port of Oslo. Consequently, their impacts are appropriately captured by including an “Oslo-dummy” in the empirical model.

Note that the total throughput of containers (loaded and unloaded) is considered an argument of the time minimization function, while the characteristics of loading/unloading operations and container types (empty/laden) are treated as contextual variables. This is to avoid that the number of parameters to be estimated become intractably large and to escape the complexity that arises when explanatory variables have zero values; see e.g. Battese (1997). Moreover, preliminary analysis shows that the model’s performance deteriorates when loaded and unloaded containers are treated as individual outputs. Our preferred modeling approach is similar to that of Battese and Coelli (1992).

Table 1: *Summary statistics*

Variable name	Description	Obs	Mean	Std. Dev.	Min	Max
Duration	Hours of ship working (per call)	1,549	12.34	8.32	0.17	62.93
Quay crane	Dummy variable (1 if more than 1 crane, 0 if not)	1,549	0.78	0.42	0.00	1.00
Containers	Containers loaded/unloaded per call (nr)	1,549	168.02	141.73	1.00	799.00
Area	Terminal area (Sq.m)	1,549	54,659.86	24,635.98	15,000.00	99,000.00
Handling eqp	Transport and stacking equipment (nr)	1,549	4.57	1.21	2.00	8.00
Spring	Dummy variable (1 if spring, 0 if not)	1,549	0.25	0.44	0.00	1.00
Summer	Dummy variable (1 if summer, 0 if not)	1,549	0.22	0.41	0.00	1.00
Autumn	Dummy variable (1 if autumn, 0 if not)	1,549	0.25	0.43	0.00	1.00
Ice	Dummy variable (1 if air temperature<0 dgr Celcius, 0 if not)	1,549	0.08	0.27	0.00	1.00
Gale	Dummy variable (1 if wind >13.9 m/s, 0 if not)	1,549	0.03	0.17	0.00	1.00
Daylight	Daylight hours per call (share of total duration)	1,501	0.55	0.35	0.00	1.00
Gross tonnage	Ship gross tonnage (GT)	1,549	8,021.79	2,340.06	1,167.00	30,567.00
Ship throughput	Containers loaded minus containers unloaded past week (capacity utilization)	1,549	-15.53	75.62	-910.00	428.00
Frequency	The individual observed ship's visit at the port this quarter (nr of vistits)	1,549	8.51	4.21	1.00	15.00
Port activity	The port's total throughput previous week (containers): Proxy for stacking of containers	1,549	1,428.81	4,413.27	0.00	26,784.00
Loading	Share of containers loaded relative to total number of containers handled per call	1,549	0.51	0.24	0.00	1.00
Empty	Share of empty containers relative to total number of containers handled per call	1,549	0.31	0.22	0.00	1.00
Simultaneous calls	Dummy variable (1 if there is more than 1 ship at berth, 0 if not)	1,502	0.26	0.44	0.00	1.00
Oslo	Dummy (1 if Oslo, 0 if not)	1,549	0.16	0.36	0.00	1.00

Note that average precipitation during the calls has also been collected, but is not included in the model because several observations are missing (i.e., reducing the number of observations for estimation substantially).

6. Results

Our dataset concerns port of calls at 9 different terminals, i.e., it has a (pseudo) panel data structure[11]. Consequently, the fixed or random effects estimators can be appropriate for modeling terminal-specific effects regarding the duration of the container handling. They reflect the terminal-specific speed of container handling, i.e., the ship working rate.
As noted in the introduction, port efficiency – comprising the ship working rate – is among the criteria for shippers' and carriers' port choices. However, when the unit of analysis is the individual port of call (and not, e.g., a year), there should be little or no loop of causation between duration of loading and unloading and variables like container volumes and ship sizes. To increase our confidence in the results, we could still address any concern about the model being vulnerable to correlations among variables that characterize the demand for port services (e.g., container volumes and ship sizes) and the port-specific effects. This problem is mitigated by the fixed effects model that exploits variation within each terminal and ignores variation between ports. However, the fixed effects model does not allow identifying the effects of variables that vary only between terminals. This is a drawback for our study, as it greatly restricts the possibilities to identify the impacts of the terminal inventories (e.g., handling equipment) on the duration of the cargo handling.
The random effects model allows modeling terminal-specific effects, but is not robust to correlations between terminal-specific effects and the independent variables. This estimator is more efficient than Ordinary Least Squares when there are terminal-specific effects, because their existence implies autocorrelation. We have implemented the Breusch and Pagan test, and find that its null-hypothesis of zero variance of the terminal-specific effects cannot be rejected. Consequently, we estimate the time minimization function using OLS, which is presented in Table 2[12]. We have also calculated it using the fixed effects estimator as a robustness check. Although the fixed effect results are not entirely comparable to the OLS results (because the fixed effect model cannot identify the effects of unidimensional variables) we conclude that the parameter estimates and standard errors are very similar. We believe this follows because important terminal characteristics, including terminal inventory, meteorological conditions, and container characteristics, are among the independent variables. This, alongside the facts that the ship working rate is only one of several criteria in port selection and that our study

[11] We are indebted to an anonymous referee for drawing our attention to the panel data structure of the sample and port selection.
[12] Results from the fixed effects and random effects estimation can be obtained from the corresponding author on request

emphasizes individual port of calls rather than aggregate demand, remedies the port selection problem.

As previously indicated, some calls have durations that are unusual. We suspect that this is due to inaccuracies or errors made by the port authorities during their data compilation and/or due to random factors that are not explained by our model specification. We therefore undertake rigorous outlier testing based on conventional outlier tests; i.e. studentized residuals, Cook's distance and the Difference in Fits (DFITS) statistic. Using 2*sqrt(k/n) as a cut-off for DFITS, we exclude 131[13] influential datapoints before re-estimating the model. Moreover, as further analysis indicates that the model is subject to heteroscedasticity, we apply robust standard errors[14]. Table 2 provides an overview of the parameter estimates, based on 1,370 observations (i.e., calls). The R^2 is 0.69.

Table 2: *Parameter estimates of the Ordinary Least Squares regression (Dependent variable: Duration)*

Variable	*Coeff (st.err)*	*Variable*	*Coeff (st.err)*
Quay crane	*-0.810****	*Ice*	*0.055*
	(0.042)		*(0.040)*
ln(Containers)	*1.218****	*Gale*	*0.025*
	(0.266)		*(0.059)*
ln(Area)	*22.737****	*Daylight*	*-0.063**
	(4.621)		*(0.033)*
ln(Handling eqp)	*7.699**	*Gross tonnage (GT)*	*-0.000***
	(4.578)		*(0.000)*
0.5ln(Containers)^2	*0.073****	*Ship throughput*	*0.000*
	(0.017)		*(0.000)*
0.5ln(Area)^2	*-2.072****	*Frequency*	*-0.007****
	(0.375)		*(0.003)*
0.5ln(Handling eqp)^2	*-0.255*	*Port activity*	*-0.000*

[13] 127 of the data points excluded based on the DFITS statistic have Cook's distance greater than 4/N.
[14] An anonymous referee requests the use of clustered standard errors to acknowledge that calls within a given terminal may be similar (and thus correlated). On the one hand, our dataset contains too few groups to successfully apply conventional clustered-robust standard errors. Moreover, we have been unsuccessful in applying alternative approaches to cluster-robust standard errors with few groups, implemented by the user-written packages clustse and wgmwildboot in Stata. On the other, important environmental characteristics such as traffic patterns, ship sizes, and meteorological conditions are explicitly modeled, thereby mitigating the importance of such (often unexplained) group differences.

	(0.435)		*(0.000)*
ln(Containers) ×ln(Area)	*-0.079****	*Loading*	*0.139****
	(0.024)		*(0.054)*
ln(Containers) × ln(Handling eqp)	*-0.091**	*Empty*	*-0.217****
	(0.047)		*(0.054)*
ln(Area) × ln(Handling eqp)	*-0.682*	*Simultaneous calls*	*0.115****
	(0.500)		*(0.029)*
Spring	*-0.034*	*Oslo*	*-0.239****
	(0.032)		*(0.084)*
Summer	*0.033*	*Constant*	*-123.438****
	(0.033)		*(27.312)*
Autumn	*0.103****		
	(0.032)		

Standard errors in parentheses: * p<0.10, ** p<0.05, *** p<0.01

Except for the variables *0.5ln(Handling eqp)²* and *ln(Area) × ln(Handling eqp)*, the parameter estimates of the Translog time minimization function (i.e., parameters 1-10 in Table 2) are all statistically significant from zero at the 10-percent level. We apply the Wald test to evaluate whether the time minimization function is i) Cobb-Douglas and ii) homothetic in outputs[15]. Both null-hypotheses are rejected at the 1-percent level.

The parameter estimates indicate that having access to more than one quay crane reduces the duration of the cargo handling by 100*(exp(-0.810)-1) = 56 percent. Next, we take the derivates of the time minimization function to identify returns to density[16] in container handling:

$$\frac{\partial \ln f(x,y)}{\partial \ln y} = \beta_y + \beta_{yy} \ln y_i + \sum_{n=1}^{N} \beta_{ny} \ln x_{ni} \qquad (6)$$

with the empirical counterpart (cf., Table 2):

[15] This amounts to testing i) whether all second-order and interaction terms of the Translog function and ii) the two interaction terms for the inputs and the container output simultaneously equal zero.

[16] We assume that the ratios of loaded to unloaded and empty to laden containers remain constant when outputs change according to Eq. 6.

$$\frac{\partial \ln f(x,y)}{\partial \ln y} = 1.218 + 0.073 \ln Container_i - 0.079 \ln Area_i - 0.091 \ln Handling\ eqp_i \qquad (7)$$

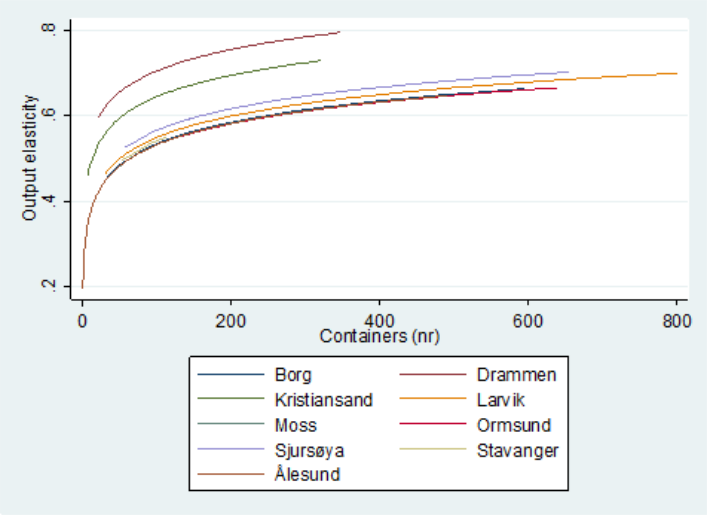

Figure 2a: *Returns to density in cargo handling (point estimates)*

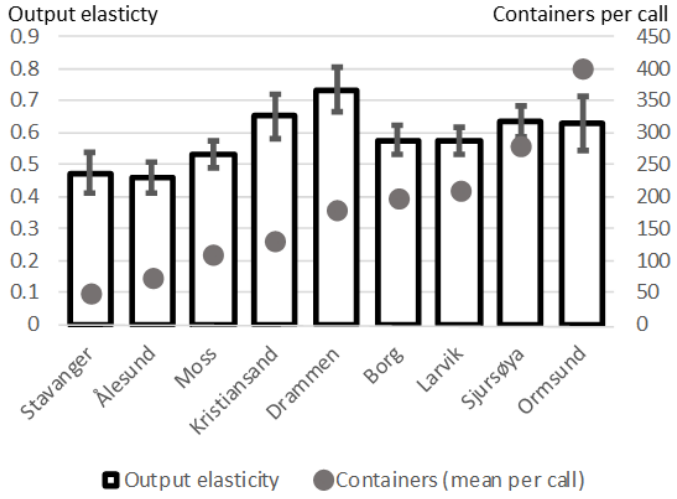

Figure 2b: *Returns to density for the mean call (point estimate and 95% confidence intervals)*

Figure 2 plots the predicted container elasticities against the number of containers handled. The left panel exhibits point estimates for observed container volumes per port, while the right panel exhibits point estimates and confidence intervals for the mean call per port. In the latter panel, the ports are sorted according to the size of their mean call.

Figure 2 shows that the predicted output elasticities are well below 1. Thus, a percentage increase in the volume of containers handled leads to less than a percentage increase in the container handling time. This means that the terminals operate under increasing returns to density, and their facilities appear sufficient for the container volumes they receive. There is consequently a potential for increasing the container throughput given the current port infrastructure, to maximize (time) productivity per call. Note that the ports of Kristiansand and Drammen appear to be closest to exhausting economies of density. They are home to the spatially smallest container terminals in the sample.

Having considered the output elasticities, we turn to the input elasticities. Formally, they are defined:

$$\frac{\partial \ln f(x,y)}{\partial \ln x_{ni}} = \beta_n + \beta_{ny} \ln y_i + \sum_{n'=1}^{N} \beta_{nn'} \ln x_{n'i} \quad (8)$$

Table 3 summarizes the input elasticities associated with the mean call (i.e., calculated at the sample mean), along with the ratio of the input elasticities for area and cargo handling equipment, respectively. The latter amounts to the marginal rate of substitution among area and handling equipment, normalized by the mean call's current input mix. Grosskopf et al. (1995) proposed this measure as an indicator of the degree of substitutability. Values of the normalized marginal rate of substitution above 1 indicate difficulty in input substitution, while values less than 1 indicate strong degree of substitutability.

Table 3: *Input elasticities for the mean call*[17]

Estimate	*Coefficient (st.err)*
Input elasticity, Area	*-0.983***
	(0.130)
Input elasticity, Handling eqp	*-0.466**
	(0.238)
Normalized marginal rate of substitution,	*2.109***
(Area /Handling eqp)	*(0.012)*

Standard errors in parentheses: * p<0.10, ** p<0.05, *** p<0.01

For the mean call, a ceteris paribus expansion of port capacity (i.e., area) is more instrumental in saving ship working time than adding container terminal transport and stacking equipment. However, there is a low degree of substitutability among the two inputs. This is also supported by the elasticities calculated at each data point, where we find the normalized marginal rate of substitutions to average at 2.348, with a standard deviation of 0.367. This suggests that substantial port productivity improvements cannot

[17] We have also calculated input and output elasticities at each data point. 264 observations (19% of the 1370 observations) exhibit positive input elasticities for area and/or handling equipment. These could be considered violations of the time minimization function's regularity conditions, as it would imply that investing in more equipment would drive loading and unloading time *upwards*, ceteris paribus. On the other hand, the output elasticities are strictly positive at each data point, which satisfies the regularity conditions and confirms our a priori expectations.

be facilitated by stand-alone investments in e.g. handling equipment, but require more comprehensive and thereby costlier investment packages.

We now turn to the contextual variables, whose parameter estimates are reported in table 2. The seasonal dummies turn out be statistical insignificant, except for the autumn dummy variable. It indicates that loading/unloading during the autumn is 100*(exp(0.103)-1) = 11 percent more time demanding than during the base quarter (i.e., the winter). This can relate to seasonal variations in the demand for maritime freight transport. The signs on the dummy variables for ice and gale both suggest that harsh weather conditions impede efficient loading/unloading, but none of them are statistically significant at the 10-percent level. The access to daylight appears to promote efficient loading/unloading, but the parameter is only statistically significant at the 10-percent level. This may indicate that the terminals under consideration have taken adequate steps to mitigate weather and visibility effects on loading/unloading operations, e.g., by ice removal and illumination.

Previous studies (e.g., Robinson (1978)) emphasize the importance of ship size for the efficiency of loading/unloading operations. Based on our available ship size measure (i.e., gross tonnage), we find that that the ship working durations per calls reduce only slightly with the size of the ship. The parameter estimate is very close to zero, but it is statistically significant at the 5-percent level. The impact of the ship's loading/unloading of cargo the past week (which approximates the ship capacity utilization) appears to have a negligible impact on the working time. The same goes for the terminal's activities (total container throughput previous week - proxy for stacking of containers). In other words, we are unable to identify decisive impacts of marginal changes in ships' and terminals' capacity utilization on the duration of the loading/unloading operations, implying that the ships and terminals have sufficient capacities to ensure efficient loading/unloading. The parameter estimate on the simultaneous call dummy indicates that the lengths of loading/unloading operations increase by 100*(exp(0.115)-1) = 12 percent when two or more ships are berthed at the same time. Thus, the scheduling of calls can be a more important measure for reducing the time which ships spend berthing than capacity expansions.

The parameter estimate on the frequency variable (number of any individual ship's visit the port this quarter, measured in number of visits) is statistically significant at the 1-percent level, and suggests that high-frequent visits to a port reduces the time it uses to load/unload cargo. This can be interpreted as a learning effect, and indicates that establishing high-frequent lines is a means to improve the ship working efficiency. Moreover, loading operations are found to be more time consuming than unloading

operations, while the handling of empty containers is less time consuming than laden containers. Thus, directional imbalances matter for the durations of the stay in port, and must consequently be considered when planning or modifying lines.

Having established the determinants of ship working productivity, we go on to consider how our model can be utilized for calculating marginal external costs of container handling. Albeit total emissions include not only emissions to air from ships at berth, but also emissions stemming from the use of machinery and trucks at the terminal, access to data prevents us from determining the latter. A comprehensive study of emissions to air by the port of Oslo[18] indicates that only eight percent of the total port-related emissions to air in Oslo are due to the land activities. A similar conclusion is reached by Berechman and Tseng (2012). Hence, it is safe to say that shipping emissions are most important, and we focus on emissions to air from ships at berth. This is done in the following steps:

1. We derive $\partial f(x,y)/\partial y$ from the parameter estimates in table 2
2. We calculate emissions to air per call (i.e., ship) per hour based on EPA's (2009) methodology. The construction of emission factors for each ship calling on Norway is described in the appendix. By multiplying these emission factors with $\partial f(x,y)/\partial y$, we obtain the change in ships' emissions to air at berth caused by the additional time required to handle the marginal container.
3. We collect damage cost estimates from the most recent Norwegian valuation study to monetize the change in ships' emissions to air due to the marginal container.

Figure 3 is divided into two panels. Panel 3a provides an overview of the auxiliary engine emission factor estimates for Nitrogen Oxides (NO_x). This panel shows that emissions to air per hour of berthing increase in ship size, here classified into small (GT < 5,000), medium (5,000<= GT < 10,000), and large (GT > 10,000) ships. Panel 3b plots the additional kilograms of NO_x emissions due to handling of the marginal container against the number of containers currently being handled per call. The figure clearly illustrates that the additional emissions are high when the volume of containers to be loaded/unloaded is low.

[18] To our knowledge, this study is only documented by the port of Oslo's fact sheet entitled "Dårlig luftkvalitet langs veien – Sjøveien er miljøveien" (Poor air quality along the road – Maritime transport is the green choice), which is available from the port's web-page (in Norwegian).

In general, smaller ships carry fewer containers and are thereby unable to reap economies of density in container handling. Despite that they have lower per hour emissions than large ships (cf. panel 2a), the additional emissions to air stemming from the handling of the marginal container are consequently higher on average for small ships than for large ships. From a Pigouvian taxation perspective, this suggests that port charges levied on cargo should be regressive, as opposed to the usual fixed tariff per container (unit of cargo). In turn, this is expected to impact on the size distribution of ships calling on Norwegian ports.

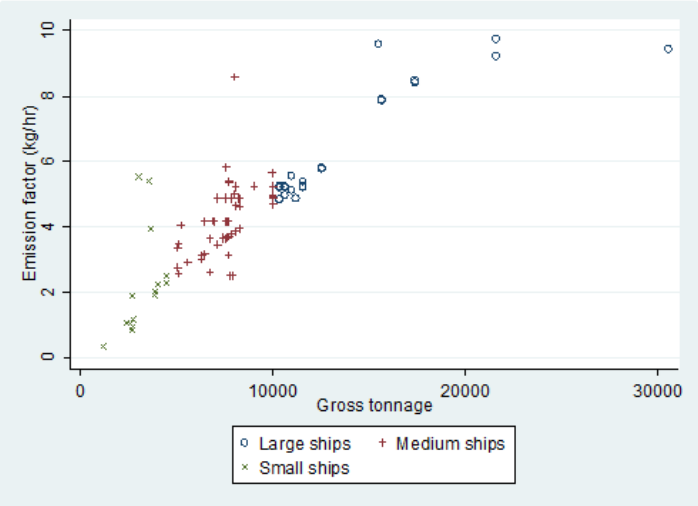

Figure 3a: *Auxiliary engine emission factors for NO_x in kilograms per hour, grouped according to ship size*

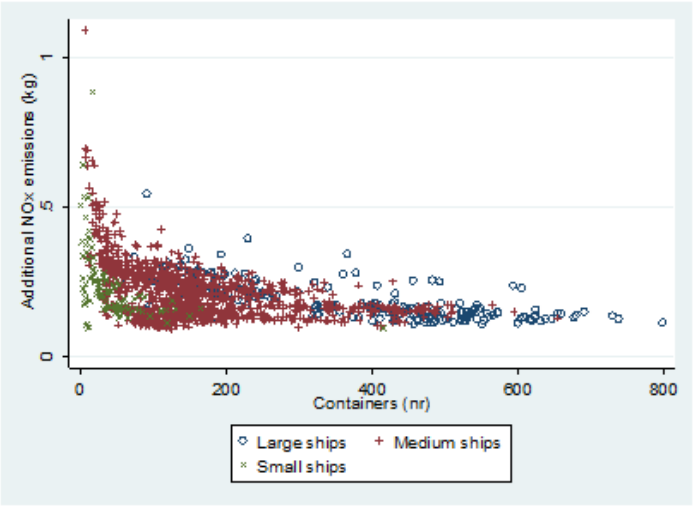

Figure 3b: *Additional NO_x emissions (kilograms) due to the marginal container, relative to the number of containers currently being loaded/unloaded*

Table 4 summarizes the damage costs per kilogram of emissions to air, based on the most recent Norwegian valuation study. We emphasize the local air pollutants NO_x and Particulate Matter (PM_{10}) because of their potent damage potential in port cities. The actual damages of a given kilogram of emissions will, of course, vary with weather conditions and the existing concentrations of air pollution in the area under consideration. It is worth noting that emissions to air from sources with high stacks – such as ships – contribute less to emission concentration than cars (Ghannam and El-Fadel, 2013), which are the focus of the valuation study. On the one hand, this could mean that the selected damage costs of emissions to air, presented by Table 4, are overstated when we consider emissions from ships. On the other hand, the cost estimates do not consider the impacts of ships' emissions to air on water quality, soil, flora, and fauna. Taking these effects into account, we consider the damage cost estimates appropriate for our study.

Table 4: *Damage costs per kilogram of emissions (2014 NOK)*

	NO_x	PM_{10}
Oslo	343	6,653
Cities with more than 100,000 inhabitants	172	2,790
Cities with less than 100,000 inhabitants	86	751

Per unit damage costs are obtained from Thune-Larsen et al. (2014), but have been inflated with the growth in nominal wage rate between 2012 and 2014 to obtain cost estimates in 2014 Norwegian krone (NOK).

Except for the Sjursøya and Ormsund terminals that are situated in Oslo, the other terminals in the dataset are located in cities with less than 100,000 inhabitants[19]. We calculate marginal external costs both if ships consume Marine Diesel Oil (MDO 1.0 % sulfur) and Marine Gas Oil (MGO 0.1% sulfur), which leads to two sets of results for PM_{10}. The consumption of the former fuel-type was in compliance with the prevailing sulfur emission standard in 2014, while the latter is in compliance with current sulfur standards for maritime transport in Norway. Multiplying the damage costs with the additional NO_x and PM_{10} emissions due to the marginal container leads to the following estimates of marginal external costs due to emissions to air associated with container handling:

Table 5: *Marginal external costs per container and tons of cargo (2014 NOK)*

Pollutant/ Port charges	*Unit of measurement*	*Mean*	*Std. Dev*	*Min*	*Max*
NO_x	per container	25.03	14.69	7.86	93.64
	per ton	3.69	37.42	0.17	1361.85
PM_{10} (MDO)	per container	11.04	11.53	2.42	60.11
	per ton	1.93	25.55	0.05	930.15
PM_{10} (MGO)	per container	4.05	4.24	0.89	22.08
	per ton	0.71	9.39	0.02	341.69
Port charges	per container	415.00	186.90	251.00	859.00

[19] Stavanger houses more than 100,000 inhabitants, but its container terminal is located at Risavika, about 8 km from the city center. According to the Norwegian national calculation tool for air quality (http://www.luftkvalitet-nbv.no), emissions in Risavika do on average not contribute to air quality degradation in the most densely populated areas in Stavanger.

External costs per ton are obtained by normalizing the marginal external cost estimates per container by the average tons of cargo per container, calculated at each data point. 22 observations exhibit fewer tons than containers, (i.e. less than 1 ton per container on average for that call), which explains the relatively high maximum values for external costs per ton of cargo. Port charges (tariffs and crane rental) are from the ports' official price lists from 2014, and may not represent actual port charges that are subject to negotiation. We were unable to find charges for Ålesund.

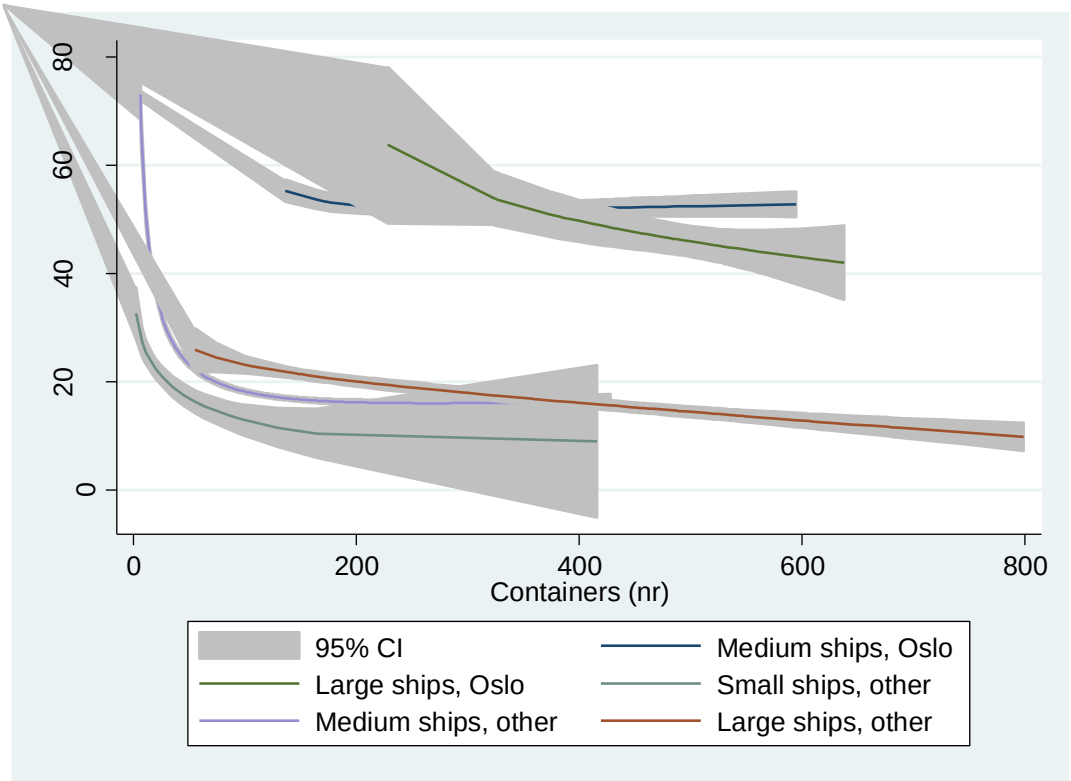

Figure 4: M*arginal external costs for NO_x per container*

Figure 4 exhibits the variation[20] in marginal external costs for NO_x across ship sizes, locations (Oslo and the other Norwegian port cities), and the container throughput. The figure clearly illustrates the importance of port localization for the magnitudes of damage costs, as Oslo is a larger and more densely populated city than the other port cities.

A recent report by Magnussen et al. (2015) presents marginal external cost estimates for freight transport by sea and rail in Norway. The report does, however, not account for external costs associated with berthing. Magnussen et al. find the external costs of maritime transport to be in the range of 0.018-0.177 NOK/ton-km[21] for small ships (GT <

[20] Figure 4 presents a twoway fractional-polynomial prediction plot for marginal external costs, constructed using the fpfitci-command in Stata.
[21] The report does not specify which type of cargo is considered.

5,000), depending on sailing in sparsely or densely populated areas. The corresponding cost range for large ships (10,000 <GT <25,000) is 0.01-0.09 NOK/ton-km. Their calculations indicate that an additional ton of cargo transported on a medium sized ship going from Oslo to Rotterdam is associated with externals costs within Norwegian waters in the range of 1.50 - 2.75 (2014-)NOK. This figure includes not only emissions to air, but also costs due to noise, accidents, and water pollution. However, it does not take the external cost of port activities due to the extra ton into account, which means that it comes *in addition* to Magnussen et al.'s estimate. For example, for medium ships in our sample berthing in Oslo, we find that the average marginal external cost of NO_X emissions associated with loading or unloading the additional ton is 14.69 NOK. We thus conclude that ignoring emissions during berthing could in many cases severely underestimate the external costs of maritime transport. However, when adding external costs stemming from loading/unloading of ships in ports, the total external costs (in Norway) per ton are still only a fraction of those that alternatively would be generated by road transport according to Magnussen et al. (2015) for the Oslo-Rotterdam example.

7. Summary and conclusions

This paper has evaluated how a broad set of factors, ranging from the container throughput and port and ship capacities and capacity utilizations to meteorological conditions and learning effects, influence the time that container ships spend at berth, being loaded/unloaded. Several policy relevant conclusions can be drawn from the empirical results.

First, size matters. The ship working rate is low for calls that load/unload few containers, probably due to high start-up "time costs" associated with a call. Carriers and shippers should therefore choose ports that can deliver a sufficient and stable supply of and demand for cargo. In the case of Norway, most ports are small and scatted. On the one hand, consolidation in the port sector is thereby a measure to promote high-quality port services. Consolidation can also pave the way for high-frequent liner services: We find indication of a learning effect, i.e., high-frequent visits to a port further reduces the time it uses to handle cargo. On the other hand, a recent study by the Norwegian transport agencies concerning consolidation in the Norwegian port sector[22] indicates that gains from

[22] See *The Norwegian National Transport Plan* http://www.ntp.dep.no/Nasjonale+transportplaner/2018-2029/Godsprosjektet (Presentation, Summary and Freight Analysis available in English).)

scale economies in the port segment are in general offset by additional road transport to and from ports. Thus, the entire transport chain must be taken into consideration when planning the development of the port sector.

Second, the type of operation (loading vs unloading) and container (empty vs laden container) matters for the duration of the cargo handling. This means that trade imbalances are important when planning a line, not only for the access to cargo, but also for the time spent in port. These factors should be considered when designing the national port system, as they can be important for its attractiveness to carriers and shippers.

Third, the findings that the time required to handle the marginal container and thereby the marginal external costs of emissions to air vary with the container throughput and the types of operations and containers handled has important implications for port pricing based on environmental principles. We show that the marginal external costs of maritime transport become severely understated when the external costs of port operations are ignored. Moreover, low density loading/unloading operations in densely populated areas are associated with high marginal external costs. From an Pigouvian taxation perspective, port tariffs should favor calls with high container throughputs. The environmental implications of such policies are reinforced if high cargo handling productivities are translated into ships' fuel savings at sea due to slow steaming between ports.

Fourth, investment in port facilities promotes efficient loading/unloading: Our empirical results suggest that port capacity expansions and increasing the stock of cargo handling equipment improve the ship working rate. From an economic point of view, resources spent on improving service quality should be reflected by a quality premium on port charges. Ultimately, carriers' willingness to pay for high-quality port services should mirror the ports' marginal costs of improving their service quality. This suggest that the current system where port charges usually are determined based on quantity should be replaced by charges based on both quantity and quality. Port charges can thereby signal the ports' service qualities to shippers and carriers. Our study provides a management guideline for the implementation of quality pricing, following along the lines of Strandenes and Marlow (2000).

Interesting venues for further research include implementing the estimated functions in the broader freight modeling framework for Norway (Madslien et al., 2015). This enables analyzing policies that not only aims to promote modal shifts, but promote socially efficient transport chains.

8. Acknowledgement

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Appendix 1

Emissions to air differ by ship type, their engine's maximum power rating, fuel type and engine load factors. We use the methodology from EPA (2009) to calculate Nitrogen Oxides (NOx) and Particulate Matter (PM10) emissions from container ships while berthed. The emissions are calculated per individual ship and across each of the 1,549 port calls.

According to EPA (2009), the emissions to air per hour of ship activity (e.g., berthed) are:

$E/A = P \times LF \times EF$

- E/A denotes emissions (by mass) of a given air pollutant per hour (g/h).
- P denotes the ship's maximum continuous rating power (kW).
- LF denotes engine load factor.
- EF denotes the emission factor for the given air pollutant (g/kWh).

The ship's maximum continuous rating power (P): The ship's maximum continuous rating power is the combined power of the main engine(s) (for propulsion) and of the auxiliary engines. We first calculate the ship's maximum continuous rating power (P), and in turn distribute the power among the main engines and the auxiliary ones. The Norwegian Costal Administration provides data about the various ships' maximum continuous rating power. This data has been made available to the project subject to a confidentiality clause. We used the merge function in Stata to connect the maximum continuous rating power data to the ship's port call data collected from Statistics Norway's port statistics. The ships'

IMO-number was used as the key variable for merging data from the The Norwegian Costal Administration and Statistics Norway. Because we emphasize emissions when the propulsion engines are shut down (ship berthed), we focus solely on emissions connected with operating the ships' auxiliary engines. Therefore, having affixed the total maximum continuous rating power per ship and port call to our dataset (Rødseth and Wangsness, 2015b), we identified the auxiliary engines' maximum continuous rating power by utilizing them to propulsion ratio (APR) for container ships, 0.220, as provided by EPA (2009).

Engine load factor (LF): To determine the auxiliary engines' power output, we apply container ship's load factor for auxiliary engines while berthed, which is 0.19 according to EPA (2009).

Emission factor (EF): The considered container ships use distillate diesel as fuel for auxiliary engines. According to the SECA14-regulation[23], which for the year 2014 applied to ships calling on ports in Norway, a maximum of 1.00 % sulphur content (by mass) in fuel was allowed. We assume that marine diesel oil with a sulphur content of max 1.00% was used across all calls. EPA (2009) recommends Entec (2002) emission factors, and - according to the Entec study - PM10 emission factor for MDO with 1.00% sulfur is 0.49 g/kWh. For NOx the emission factor is 13.9 g/kWh (EPA, 2009). We have also re-estimated the emissions considering marine gas oil with a sulfur content of 0.1 %. In this case, the PM10 emission factor is 0.18 g/kWh.

Appendix 2: Additional summary statistics (for the year 2014)

Terminal	*Containers (nr)*	*Calls (nr)*	*Ships (nr)*	*Area (m2)*	*Quay cranes (nr)*	*Yard cranes (nr)*	*Straddle carriers (nr)*	*Handling eqp. (nr)*
Borg	31041	156	28	60000	3	0	0	5
Drammen	15507	87	6	20000	2	0	0	2
Kristiansand	31484	242	31	15000	2	0	0	5
Larvik	49857	236	27	50000	2	0	0	5
Moss	26491	240	24	80000	2	0	0	4
Ormsund	45325	113	6	36550	2	4	0	8
Sjursøya	36131	129	3	51868	2	0	5	4
Stavanger	1119	23	8	99000	1	0	0	3
Ålesund	23307	323	31	80000	1	0	0	4

[23] Sulphur Emission Control Areas (SECA) are sea areas in which stricter controls are effected to minimize airborne emissions (e.g. SOx and NOx) from ships. International Maritime Organization's Sulphur oxides (SOx) and Particulate Matter (PM) – Regulation 14. Available at: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)-%E2%80%93-Regulation-14.aspx.