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# Noise pollution of container handling: External and abatement costs and environmental efficiency

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## Highlights

- Fills research gap regarding marginal external noise costs of terminal operations.
- First treatment of non-material pollutants in environmental production analysis.
- Development of a generic production analysis framework for noise pollution.
- Empirical analysis of container handling within the port of Oslo, Norway.
- Estimation of marginal external and abatement costs and environmental efficiency.

## Abstract

While previous studies have pointed to their economic significance, terminal operations are frequently ignored in transport appraisal and policy analysis. This paper develops a generic model framework for estimating noise emissions from container terminal operations to derive key metrics for port policy analysis. A novel microeconomic production model that accommodates basic acoustics is proposed. Based thereon, abatement costs are derived using optimization and marginal external costs and efficiency scores are estimated using panel data frontier estimation. The virtues of the modeling approach are illustrated using noise meter readouts combined with port activity and meteorological data from the port of Oslo, Norway.

Previous

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## Keywords

Environmental production analysis; Container port; Acoustics; Abatement costs; External costs

JEL classification

D24; Q53; C51; R41

## 1. Introduction

While providing substantial benefits, transport is also accompanied by damage costs. Optimal transport policies seek to balance these costs and benefits (Wangsness et al., 2020). Multimodal transports – which have for a long time been viewed as a sustainable alternative to road freight transport – are often accompanied by terminal activities in densely populated areas (Rødseth et al., 2020). Focusing on emissions to air, Rødseth et al. (2018) find maritime transport costs to be severely underestimated when external costs of port operations are ignored. This holds for transport cost-benefit analysis in Norway, which means that the relative social cost of road and multimodal transports is potentially biased and can lead to inefficient prioritization of infrastructure projects. As studies documenting the external costs of cargo handling operations are lacking (Vierth et al., 2019), more work is needed to determine the costs which terminal operations inflict upon their surroundings. To enable cost-benefit assessment of transport policies, new information about the potential for and costs of mitigation of externalities is also required.

This paper contributes to filling the identified research gap by extending the scope of Rødseth et al.'s (2018) analysis to one of the best known and harmful nonmaterial pollutants; unwanted and harmful sounds, known as *noise*. It is caused by transport and industrial activities, and provokes stress reactions, sleep-stage changes, and clinical symptoms such as hypertension and cardiovascular diseases that contribute to premature mortality. According to the European Environment Agency,[1] noise pollution results in at least 10,000 cases of premature deaths in the EU each year.

Noise is high on the port policy agenda: Alongside emissions to air, noise is considered one of the top environmental priorities of European ports.[2] The main contribution of this paper is the development of a generic model framework for estimating noise from container terminal operations that enables estimation of key metrics for port policy analysis: Marginal external noise costs; Noise abatement costs; and Environmental efficiency. The aim has been to provide a simple and applicable framework that helps circumvent the unjust treatment of terminal operations in transport appraisal and policy analysis. Using suitable data, the framework could also be adapted to other types of freight terminals. The framework offers decision support to policy makers and port managers by offering insights into the external costs of port operations and the potentials for and costs of noise mitigation. The framework can also be applied as an input to port pricing.

First, a novel microeconomic production model that incorporates basic acoustics while accommodating traditional neo-classical (mean-valued) production analysis, Stochastic Frontier Analysis (SFA) or Stochastic Non-parametric Envelopment of Data (StoNED) is proposed. The focus is on situations where noise meter measurements are available and where noise emanates from multiple sources. This paper explores how aggregation of noise from many sources may guide the choice of functional form of parametric production models.

Second, the virtues of the proposed modeling approach are proven by an empirical study of container handling within the port of Oslo (Norway's capital). In Norway, several of the largest ports – including the port of Oslo – are situated in city centers, thus posing an imminent threat to the adjacent population. The model is fitted using noise meter readout combined with port activity and meteorological data. Based on the empirical model, abatement costs are derived using optimization and marginal external costs and efficiency scores are estimated using panel data frontier estimation.

The plan of the paper is as follows. Section 2 reviews the literature on environmental efficiency measurement and basic concepts in acoustic theory while Section 3 discusses how to imbed the latter in an environmental production model. Section 4 presents an overview of the data and the empirical results while Section 5 discusses marginal external costs, shadow prices, and environmental efficiency. Section 6 concludes.

## 2. Background

This section briefly reviews the literature on environmental production analysis and outlines the theoretical foundations of the production model framework developed in Section 3.

### 2.1. Environmental production analysis

Well-informed policy making requires suitable tools for estimation of key parameters such as marginal external and abatement costs and environmental efficiency. Lee et al. (2014) identify two primary approaches for estimating the value of an externality: Economics and engineering. They differ regarding scope, methodology, and data requirements, and both have their pros and cons. This paper aims to combine the virtues of both approaches. It is rooted in the economic production (aka productivity and efficiency) analysis tradition, which is an emerging field in the analysis of externalities. Kuosmanen and Zhou (2021) attribute the popularity of this approach to its strong axiomatic foundation in economic production theory and its ability to let the data “speak for themselves”.

Because of their increased emphasis on modeling pollutants, production-theoretic studies have attempted aligning the production model with physical or engineering models to achieve a more accurate description of the pollution-generating process. The emphasis has been on incorporating the materials balance principle into the production analysis framework; e.g., Førsund (2009), Lauwers (2009), and Rødseth (2017).

Environmental production analysis' area of application is not limited to material pollutants such as sulfur and carbon dioxides from fossil fuel combustion (cf. Färe et al., 2005) or nitrogen byproducts from pig farming (cf. Coelli et al., 2007), but also comprises non-material pollutants such as noise, radiation, and thermal pollution. One of the questions raised in the plenary discussions during the parallel sessions on externalities at the 15th European Workshop on Efficiency and Productivity Analysis (EWEPA) concerned how to deal with non-material pollutants in environmental production analysis. This paper attempts a first reply to this important research question by extending the scope of environmental production analysis to noise pollution.

As noted by Martini et al. (2013), incorporating decibels (i.e., a logarithmic sound intensity level, abbreviated dB) in production analysis may be problematic because the conventional production model considers linear combinations – associated with the well-known convexity axiom – of logarithms to be feasible. The weak disposability axiom (Shephard, 1970) – often seen as a *one-size-fits-all* approach to model undesirable outputs in production analysis – is vulnerable to the same remark. However, as noted by Martini et al. (2013), projecting noise onto a linear scale is less useful as the differences in noise levels may be so large that any comparison is meaningless.

Modeling of noise pollution as an undesirable output in productivity and efficiency analysis is not widespread, and most applications are in the field of airport productivity measurement. Only a few of these studies (e.g., Martini et al., 2013; Scotti et al., 2014) include noise levels in the empirical production model. Other studies use indirect noise measures including monetary measures such as noise fees (e.g., Yu, 2004; Yu et al., 2008) or variables characterizing noise regulation, such as noise contours[3] (e.g., Voltes-Dorta and Martín, 2016) and noise budgets and limits to hours of airport operations (e.g., Gillen and Lall, 1997). Contrary to this paper, previous productivity and efficiency analyses pay no attention to acoustic theory when developing their model frameworks.

## 2.2. Basic acoustics

Noise refers to an undesirable sound.[4] Sound is a variation of density in the air. A sound source radiates acoustic power that results in a sound pressure. Acoustic energy flows are known as sound intensities[5] and are measured in Watts per square meter ($W/m^2$). The span between the weakest and the most powerful sounds that the ear can catch without inflicting pain is $10^{-12}$ to $1\,W/m^2$. Most sounds experienced in daily life are below $0.01\,W/m^2$, while some (potentially painful) sounds are greater than 0.

As noted by Martini et al. (2013), the huge differences between sound levels make the linear scale less useful for production modeling/efficiency analysis. The linear scale also makes it difficult to illustrate sound intensities in a way that resembles the characteristics of hearing. Consequently, the sound intensity, denoted $i \in \mathfrak{R}_+$, is frequently converted into a logarithmic sound intensity level, $L \in \mathfrak{R}_+$, measured in decibels:

$$L = 10\ \log_{10}\left(\frac{i}{i_{ref}}\right) \tag{1}$$

where $i_{ref} = 10^{-12}$ such that $L = 0$ for any sound that is on the brim of hearing, and log refers to the base-10 logarithm.

The log-transformation must be considered by the production analysis. Available noise data are measured in decibels, and it is tempting to incorporate the sound level into the production model in the same way as any other undesirable output (e.g., carbon or sulfur dioxides). However, this leads to erroneous conclusions. Consider for example the convexity axiom, which is a standard building block of production models: It states that if, say, the sound intensities $10^{-4}$ and $10^{-6}$ are included in the technology, so are their convex combinations. Fig. 1 presents the convex combinations of the two sound intensities after converting the results to decibels (the blue line). The results are compared with the convex combinations of the two dB levels (the red line).

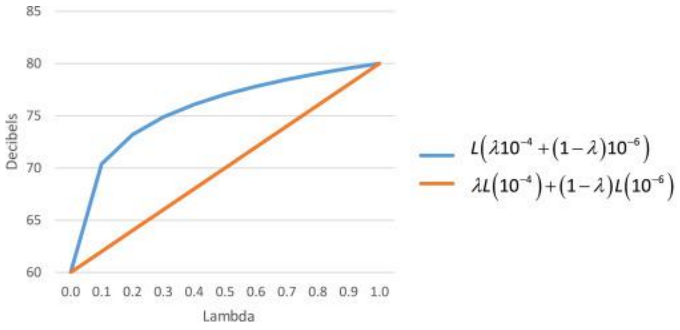


Fig. 1. Convex combinations of sound intensity levels.

Fig. 1 illustrates that, when converted to decibels, the convex combination of the two sound intensities is non-linear. Thus, merely taking (linear) convex combinations of the two initial sound intensities as in Martini et al. (2013) is inappropriate. The modeling approach proposed in Section 3 solves this problem.

Sound intensity decreases with the distance from the source to the receiver of the sound, because the energy is distributed across an increasingly large area as the energy flows from the source. In the case where there are no reflections or reverberation the sound intensity will obey the inverse square law. Let $d \in \mathfrak{R}_+$ denote the distance from the source to the receiver and let $p \in \mathfrak{R}_+$ denote the source's acoustic power in Watts. The following relationship then applies:

$$i = \frac{p}{4\pi d^2} \tag{2}$$

The assumption of a free field is not appropriate in real life as sounds will be reverberated differently by different ground materials, as well as affected by obstacles between the source and the receiver. Nevertheless, the sound distance adjustment $1/g(d)$ - where $g(d) = 4\pi d^2$ in a free field – can conveniently be assumed to be decreasing concave. In the empirical application, the power of the distance is assumed to be an unknown parameter to be estimated; i.e., $g(d) = 4\pi d^{\beta_d}$, where $\beta_d$ is the parameter. The higher the parameter value, the stronger the attenuation of sound.

Meteorological conditions play a role in the transfer of sound from the source to the receiver. First, sound waves move faster in warm air than in cold air because it is less dense. On a sunny day when the air is warmest near the ground and colder at higher altitudes, the temperature gradient causes the sound wave to move away from the ground and is consequently less harmful to the adjacent population. In the evening, this relationship is reversed. Consequently, an increase in temperature will lead to a decrease in the sound level at the receiver. Second, dry air absorbs more acoustical energy than moist air, implying that an increase in humidity will increase the sound level at the receiver. Third, wind is the predominant cause of motion of air in a certain direction. As a sound wave travels through air, the speed of sound depends both on the speed of the wave and the speed of wind. Windspeed gradients affect the path which sound travels through air. *Refraction* means that sound waves bend towards regions of lower sound speed. As windspeed tends to increase with the distance from the ground, sound refracts downward when moving downwind and upward when moving upwind. I include these contextual factors in the environmental production model that incorporates noise pollution, which is proposed in Section 3.

Thus far, discussions have concerned noise stemming from a single source. This is, however, a special case as a receptor is frequently exposed to sounds from a wide range of sources. When aggregating sound from multiple sources one must consider if different sound waves are aligned in a fixed phase relationship (known as *coherence*) or not. In general, sounds from different sources will have no phase relationship. On some occasions they align, on others they don't. Hence, assuming incoherence suffices. When multiple incoherent sounds occur simultaneously, the intensities of the sounds add together. Thus, if incoherent sounds from $K$ sources reach a recipient simultaneously, the sound level at the recipient is:

$$L = 10\ \log_{10}\left(\frac{\sum_{k=1}^{K} i_k}{i_{ref}}\right) \tag{3}$$

## 3. The environmental production model

Section 2 provides guidance for the specification of an environmental production model that incorporates noise pollution. In line with acoustic theory, the model should satisfy the following 4 criteria.

i) decibels are log-transformed sound intensities

ii) sound decays with distance

iii) contextual variables affect the sound level at the receiver

iv) sounds from different sources should be added when they are incoherent

Let $z \in \mathfrak{R}_+^N$ denote contextual variables and let $y \in \mathfrak{R}_+$ denote the intended output, i.e., the number of containers to be loaded/unloaded in this paper. The acoustic power at the source in Eq. (2) is defined by the function $f(y)$. Finally, $\varepsilon$ denotes the error term that is composite in frontier analysis. That is, $\varepsilon = u + v$, where $u$ is the efficiency measure that describes excess noise relative to best practices and $v$ captures random noise. In the literature on stochastic frontier estimation, the two error term components are assumed to be independently distributed: The noise term is assumed to be normally distributed, while the efficiency term is non-negative and follows a one-sided distribution.

The subsequent empirical analysis utilizes hourly data on noise emissions and cargo handling activities. Because the port of Oslo is not very busy, there is typically a gap between departures and arrivals of vessels. Hence, consecutive hours when there are one or more vessels at berth is herein dubbed a "call". Because a call typically lasts for multiple hours, the dataset has a panel structure where panel identifier (denoted *j*) concerns individual calls while the time variable (denoted *s*) is hour. This data structure is exploited to estimate a composite error with call-specific efficiency term $\varepsilon_{j,s} = u_j + v_{j,s}$, where $u_j$ is often dubbed time-invariant efficiency in the literature.

Consider the environmental production model in Eq. (4) that satisfies criteria i)-iv):

$$i_{j,s} = \sum_{k=1}^{K} \left( \frac{f(y_{k,j,s})}{g(d_k)} \right) 10^{\beta_0 + \sum_{n=1}^{N} \beta_{z,n} z_{n,j,s} + u_j + v_{j,s}} \tag{4}$$

where *k* indexes quay (location), *j* indexes call, and *s* indexes hour. The model can be transformed in the following way using Eq. (1):

$$\frac{L_{j,s} - 120}{10} = \beta_0 + \log_{10} \sum_{k=1}^{K} \left( \frac{f(y_{k,j,s})}{g(d_k)} \right) + \sum_{n=1}^{N} \beta_{z,n} z_{n,j,s} + u_j + v_{j,s} \tag{5}$$

The dependent variable can be considered a normalization of the logarithmic sound intensity level, relative to the reference level used for converting sound intensities into decibels.

Eq. (5) has obvious similarities to model specifications used in parametric and semi-parametric efficiency analysis. While the use of both parametric and non-parametric benchmarks for sound intensity are discussed in the following, this study focuses on parametric modeling.

For the parametric specification, a functional form of the sound intensity norm must be selected by the researcher. Based on its appropriate fit to the data used for the subsequent empirical analysis, an exponential (Cobb-Douglas type) functional form for the sound intensity function $f(y)$ is here considered. In this case, the empirical counterpart of Eq. (5) is:

$$\frac{L_{j,s} - 120}{10} = \beta_0 + \log_{10} \sum_{k=1}^{K} \left( \frac{y_{k,j,s}^{\beta_y}}{4\pi d_k^{\beta_d}} \right) + \sum_{n=1}^{N} \beta_{z,n} z_{n,j,s} + u_j + v_{j,s} \tag{6}$$

More complex functional forms such as the Translog function that involve squared and interaction terms may of course also be considered. A flexible functional form is not used in this paper because preliminary testing rejected its superiority for the empirical application.

Alternatively, the noise norm can be estimated non-parametrically. A benefit of this approach, compared to the parametric approach, is that regularity conditions such as monotonicity and curvature constraints (cf., Fig. 1 and the related discussion) can be imposed globally on the noise function. However, non-parametric estimation complicates the analysis and is therefore not utilized as the main approach of this paper. A novel extension of Convex Non-parametric Least Squares for noise estimation can be found in Appendix A.

### 3.1. Linearization

Note that Eq. (6) becomes a linear regression model when there is only one noise source, i.e., when *K*=1.

$$\frac{L_{j,s} - 120}{10} = \beta_0 + \log_{10} \left( \frac{y_{j,s}^{\beta_y}}{4\pi d^{\beta_d}} \right) + \sum_{n=1}^{N} \beta_{z,n} z_{n,j,s} + u_j + v_{j,s} \quad \Leftrightarrow \tag{7}$$

$$\frac{L_{j,s} - 120 + 10 \log_{10}(4\pi)}{10} = \underbrace{\left(\beta_0 - \beta_d \log(d)_{10}\right)}_{\text{Constant}} + \beta_y \ \log_{10}(y_{j,s}) + \sum_{n=1}^{N} \beta_{z,n} z_{n,j,s} + u_j$$

$$+ v_{j,s}$$

### 3.2. Efficiency measurement

The β-parameters discussed above characterize the properties of the sound intensity norm. This frontier can be interpreted as the minimal feasible level of noise given the amount of container handling and contextual variables. Inefficiencies in cargo handling can, however, lead to excess noise relative to best practices. More precisely, if the error term component $u_j$ has a positive expectancy, the term $10^{u_j}$ in Eq. (4) measures deviation from the sound intensity norm. Hence, it is an environmental efficiency measure.

The dataset presented in Section 4 has a panel structure in the sense that the timespan of each call (including calls where ships are jointly berthed in Ormsund and Sjursøya) can be identified. Consequently, panel data methods for efficiency measurement can be used to disentangle environmental efficiencies, i.e., to estimate the component $u_j$ of the composite error term $\varepsilon_{j,s}$ defined in the previous equations. This provides a score per call that takes the value 1 if noise cannot be reduced and a value *less than* 1 if noise can be reduced for the given amount of container handled, i.e., relative to the cost norm. Herein, Schmidt's and Sickles' (1984) approach to efficiency measurement using panel data is applied. This approach assumes time invariant efficiency scores. Compared to most other approaches in stochastic frontier analysis, this method comes with the virtue that the efficiency term can be identified without making any distributional assumptions. Efficiencies are calculated by i) for each call *j*, taking averages of error terms $\varepsilon_{j,s}$ per time span *s*=1,..,*S* comprised by this call, ii) identifying the minimum average error of all *j*=1,..,*J* calls in the dataset, iii) calculating the difference between the average error per call and the minimum average error (considering all calls), and iv) deriving each efficiency score by taking the inverse of 10 raised to the power of the result of step iii per call.

### 3.3. Marginal external costs

Marginal external cost analysis is a prerequisite for efficient environmental policy and has become the backbone of EU's transport policy. Marginal external noise costs are standard in transport appraisal, but the emphasis is predominately on road and rail transport. Indeed, the European Commission's handbook on estimation of the marginal external costs of transport (van Essen et al., 2019) puts little emphasis on noise due to waterborne transport, and valuation methods targeting port noise are scarce.

Focusing on road and rail transport, Andersson and Ögren (2011, 2013) developed a model framework for estimating marginal noise costs. Recently, Swärdh and Genell (2020) extended this approach by among other considering time-of-day differencing of noise charges. Whilst building on these novel contributions, a fundamental difference between them and the current study is that the former lean on noise measurement by complex noise propagation models that require costly subscription and training. This paper offers a low-cost alternative based on statistical analysis.

Note that the subsequent discussion simplifies the mathematical notation by ignoring the index for calls ($j$=1,..$J$). This is because the panel structure of the dataset is important for estimation of the noise benchmark and for efficiency assessment, but not for the subsequent analyses of marginal external and abatement costs.

Noise regulation and marginal external cost estimation are based on the average noise level over a given period. $L_{\text{den}}$, a weighted average of the sound level per hour of the day, is a common metric in noise regulation. It imposes penalties of 5 and 10dB in the evening and at night, respectively, to approximate that sounds that occur when recipients are at home and/or asleep are more annoying and harmful than sounds occurring at daytime. Formally, the $L_{\text{den}}$ measure is defined:

$$L_{den} = 10\ \log_{10}\left(\frac{1}{24}\left(\sum_{s=7}^{18} 10^{\frac{L_{eq,s}}{10}} + \sum_{s=19}^{22} 10^{\frac{L_{eq,s}+5}{10}} + \sum_{s=23}^{6} 10^{\frac{L_{eq,s}+10}{10}}\right)\right), s = 1, ..,24 \tag{8}$$

Consequently, the contribution of an additional container in location $k$' and hour $s$' to $L_{\text{den}}$ is:

$$\frac{\partial L_{den}}{\partial y_{k',s'}} = \frac{\partial L_{den}}{\partial L_{eq,s'}} \frac{\partial L_{eq,s'}}{\partial y_{k',s'}} \tag{9}$$

Expressions for the first component are found by taking the derivative of Eq. (8):

$$\frac{\partial L_{den}}{\partial L_{eq,s'}} = \frac{10^{\frac{L_{eq,s'}}{10}}}{\sum_{s=7}^{18} 10^{\frac{L_{eq,s}}{10}} + \sum_{s=19}^{22} 10^{\frac{L_{eq,s}+5}{10}} + \sum_{s=23}^{6} 10^{\frac{L_{eq,s}+10}{10}}} \quad \text{(Day)}$$
$$\frac{\partial L_{den}}{\partial L_{eq,s'}} = \frac{10^{\frac{L_{eq,s'}+5}{10}}}{\sum_{s=7}^{18} 10^{\frac{L_{eq,s}}{10}} + \sum_{s=19}^{22} 10^{\frac{L_{eq,s}+5}{10}} + \sum_{s=23}^{6} 10^{\frac{L_{eq,s}+10}{10}}} \quad \text{(Evening)}$$
$$\frac{\partial L_{den}}{\partial L_{eq,s'}} = \frac{10^{\frac{L_{eq,s'}+10}{10}}}{\sum_{s=7}^{18} 10^{\frac{L_{eq,s}}{10}} + \sum_{s=19}^{22} 10^{\frac{L_{eq,s}+5}{10}} + \sum_{s=23}^{6} 10^{\frac{L_{eq,s}+10}{10}}} \quad \text{(Night)} \tag{10}$$

For the parametric production model, an expression for the second component is found by taking the derivative of Eq. (6):

$$\frac{\partial L_{eq,s'}}{\partial y_{k',s'}} = \frac{10}{\ln(10)}\left(\frac{\beta_y}{y_{k',s'}} \frac{\frac{y_{k',s'}^{\beta_y}}{4\pi d_{k'}^{\beta_d}}}{\sum_{k=1}^{K}\left(\frac{y_{k,s'}^{\beta_y}}{4\pi d_k^{\beta_d}}\right)}\right) \tag{11}$$

which collapses into

$$\frac{\partial L_{eq,s'}}{\partial y_{k',s'}} = \frac{10}{\ln(10)}\left(\frac{\beta_y}{y_{k',s'}}\right) \tag{12}$$

when only quay $k$' is operative in hour $s$'.

Having obtained the contribution of a marginal container to $L_{\text{den}}$, marginal external costs can be calculated by multiplying it with the number of persons exposed to port noise and a monetary measure of noise costs per persons per dB. When considering damage costs, it is common to assume that all residents that face an outdoor $L_{\text{den}}$ above a given threshold are negatively affected by the noise. The Norwegian valuation study (Magnussen et al., 2010) recommends a unit price of 365 Norwegian (2014)kroner per dB(A) per affected person per year, where being affected means being exposed to a daily average sound level of 55dB(A) or more.

The assumption of a linear damage cost can be challenged. On the one hand, Magnussen et al. (2010) undertake a re-evaluation of data from Norwegian respondents participating in the well-known HEATCO study using statistical methods. Among key findings of Magnussen et al.

(2010, p. 23) is that “there are no significant relationships among categories of nuisance and increasing noise” (own translation from Norwegian). Thus, the uniform damage cost is empirically founded. On the other hand, the European Union's handbook on external cost of transport (van Essen et al., 2019, p. 94) notes that “HEATCO assumes a constant valuation per dB of noise for annoyance costs, which has recently been disputed. This Handbook therefore uses increasing prices per dB based on the most recent insights..” However, the handbook does not provide damage cost estimates for noise related to maritime transports.

Bearing this caveat in mind, the subsequent analysis assumes a linear damage cost function. This can be defended both from the perspective that the linear function passes a set of statistical tests, and because – as the subsequent analysis will show – the difference in the average noise level with minimum and maximum port activity is limited. This means that the probability that a person changes decibel or nuisance group (i.e., faces a higher damage cost) as a result of increasing container handling activities is limited.

## 3.4. Abatement costs

The port of Oslo monitors noise because its activities are subject to a noise regulation that the (year-average) $L_{den}$ cannot exceed $L^*_{den}$ (i.e., 55 dB). It may carry compliance costs in the sense that it can restrain the overall container handling, may coerce the port into shifting its cargo handling to hours and days when it is costlier (e.g., because of special salary agreements), and/or may induce container handling at less suitable locations (i.e., at quays which are situated furthest away from the adjacent population). The container handling in Oslo is distributed among the Ormsund and Sjursøya terminals, but they are disproportionally in use.

Let $r \in \Re_+$ denote the total charge per container handled. Consider the following optimization problem, in which port revenues are maximized subject to the noise regulation and production technical constraints:

$$\max_{y} \left\{ \sum_{k=1}^{K} \sum_{s=1}^{24} r y_{k,s} : \sum_{k=1}^{K} \sum_{s=1}^{24} y_{k,s} \le Y_{\max}, L_{den} \le L^*_{den} \right\} \tag{13}$$

where $Y_{\max}$ is the technical limit to the number of containers that can be handled per day. Eq. (13) is a non-linear optimization problem due to the noise function and the $L_{den}$ constraint. This causes convergence problems for the model in Eq. (13), and the following linearization is therefore considered:

- Based on the observed data to be outlined in Section 4, the following technical production limits are assumed for the container port of Oslo:
  - a technical limit of 982 containers handled per day
  - a technical limit of 32 containers handled per quay per hour
  - a maximum of three quays in operations per hour
- Using predictions of noise levels based on the empirical production analysis, three 1,089×33 noise matrices (denoted $\boldsymbol{L_d}$, $\boldsymbol{L_e}$, and $\boldsymbol{L_n}$, with reference to noise levels during the day, evening, and night) associated with container handling at the Ormsund (up to 1 quay in operation) and Sjursøya (up to 2 quays in operation) container terminals are constructed alongside the 1,089×33 matrix containing the corresponding container volumes used for noise prediction (i.e., integers, ranging from 0 to 32 containers per quay per hour).
- Prior to optimization, noise levels are linearized (i.e., all elements are transformed by 10^($L_s$/10)), after including penalties for noise events in the evening (5 dB) and at night (10 dB).

In total, 1,089×33 = 35,937 possible combinations (i.,e., 33 possible levels of cargo handling –including the option of 0 containers handled – per quay. For Sjursøya, this gives 33×33 possible combinations) of container handling at the Sjursøya and Ormsund terminals are considered. Intensity variables $\lambda_{j,\tilde{s}}$, where $j$ here indexes the 35,937 possible combinations and $\tilde{s}$ indexes time of day (i.e., day, evening, night), are used to maximize the container output subject to constraints. For simplicity, the linearized model comprises *one representative hour* each for containers handling during the day, evening, and night, respectively, and multiplies the number of containers handled per hour with the duration of the day, evening, and night, measured in hours. The following linear integer program maximizes the container throughput subject to the technical production and $L_{\text{den}}$ constraints:

$$\begin{aligned}
&\max_{\lambda,y} 12y_{day} + 4y_{evening} + 8y_{night} \\
&s.t. \\
&12y_{day} + 4y_{evening} + 8y_{night} \leq 982 \\
&\textstyle\sum_{j=1}^{35,937} \lambda_{j,\tilde{s}}\, y_j = y_{\tilde{s}}\,, \forall \tilde{\mathrm{s}} \in (day, evening, night) \\
&\textstyle\sum_{j=1}^{35,937} \lambda_{j,\tilde{s}} = 1, \forall \tilde{\mathrm{s}} \\
&\lambda_{j,\tilde{s}} \in \{0,1\}\,, \forall \mathrm{j}, \tilde{\mathrm{s}} \\
&\textstyle\sum_{j=1}^{35,937} \lambda_{j,d} 10^{\left(\frac{L_{j,day}}{10}\right)} + \sum_{j=1}^{35,937} \lambda_{j,e} 10^{\left(\frac{L_{j,evening}+5}{10}\right)} + \sum_{j=1}^{35,937} \lambda_{j,n} 10^{\left(\frac{L_{j,night}+10}{10}\right)} \\
&\leq 10^{(L_{den}^{*}/10)}
\end{aligned} \tag{14}$$

The maximum of Eq. (14) is readily comparable to the technical production capacity (i.e., 982 containers daily) of the port. Deviations from the maximum represent abatement costs, i.e., forgone output because of the noise regulation.

## 4. Dataset and empirical implementation

Data on port noise are scarce. For Norway, the main exception is data from the port of Oslo, which continuously monitors noise emissions related to container handling. The port has installed noise meters at two strategic locations in Oslo; Ormøya and Bekkelagsskråningen. These meters will, of course, pick up noise from other sources than the port, but this bias appears to be more prominent for Bekkelagsskråningen than for Ormøya. More people are also likely to be affected by port noise at Ormøya compared to Bekkelagsskråningen. Hence, the empirical study focuses on data from the noise meter at Ormøya, which targets noise events related to container handling at the Ormsund and Sjursøya container terminals. Fig. 2 shows the locations of the two container terminals and Ormøya, which are all situated in the city centre of Oslo.

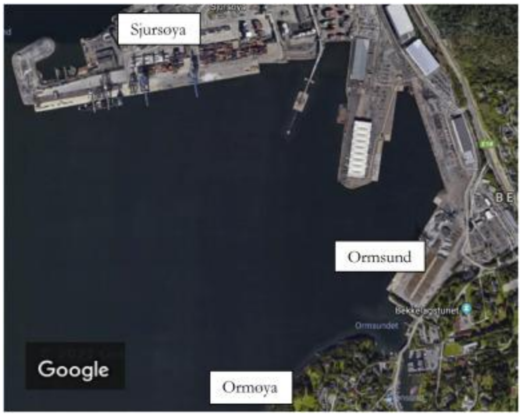


Fig. 2. Exhibiting the locations of the Sjursøya and Ormsund container terminals and the sound meter at Ormøya.

Source: **Google Maps™ mapping service**

The port of Oslo publishes the results of their noise measurement (per hour) at their web site. Unfortunately, the results are not available in numeric form, but are only published as weekly line charts. The web-based tool WebPlotDigitizer is used to extract the data, focusing on noise pollution related to container ships arriving in Oslo during the first quarter of 2014. This is motivated by seasonal variations in the sound level at Ormøya, as sounds related to gardening, leisure, and birds increase in intensity during the spring and summer. Fig. 3 illustrates the variation in the outdoor sound level ($L_{\text{Aeq, 1hr}}$) at Ormøya over the first quarter of 2014.

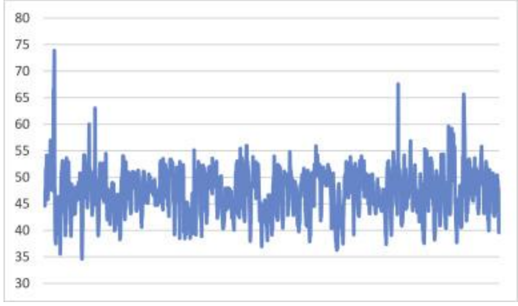


Fig. 3. Variation in the sound level (dB) per hour measured at Ormøya in the 1st quarter of 2014.

The noise measurement data is merged with Statistic Norway's port statistic[6] that contains information about the arrival and departure times of ships calling on Sjursøya and Ormsund. The container port at Sjursøya comprises three quays in use, while the Ormsund terminal comprises two quays in use in the first quarter of 2014. The port statistic allows pinpointing the quays used and specifies the total number of containers being loaded/unloaded per vessel. However, it does not report the number of containers being loaded/unloaded *per hour*. A uniform distribution is assumed when predicting the number of containers loaded/unloaded per hour.

Information about the distances from the five quays to the receiver (i.e., the noise meter at Ormøya) and hourly information about meteorological conditions are appended to the dataset. The latter is obtained from the web-page Yr.no's historical weather database. Using hourly data, there are 2,141 observations in the dataset in total. Table 1 provides summary statistics of the most important variables.

Table 1. Summary statistics.

| **Variable** | **Nr. obs** | **Mean** | **St. Dev** | **Min** | **Max** |
|---|---|---|---|---|---|
| $L_{\text{Aeq, 1hr}}$ | 2,141 | 47.47 | 4.25 | 34.61 | 73.87 |
| Containers per hour, S1 | 2,141 | 2.81 | 6.59 | 0.00 | 29.80 |
| Containers per hour, S2 | 2141 | 1.78 | 6.00 | 0.00 | 28.03 |
| Containers per hour, S3 | 2,141 | 2.86 | 6.01 | 0.00 | 35.30 |
| Containers per hour, O1 | 2,141 | 0.06 | 0.65 | 0.00 | 7.08 |
| Containers per hour, O2 | 2,141 | 7.39 | 11.64 | 0.00 | 40.43 |
| Avg. Temp (°C) | 2,141 | 0.99 | 4.64 | −13.60 | 15.10 |
| Moisture (%) | 2,141 | 0.83 | 0.16 | 0.15 | 1.00 |
| Avg. Wind (m/s) | 2,141 | 2.86 | 1.41 | 0.20 | 8.00 |
| Southern wind (dummy) | 2,141 | 0.54 | 0.50 | 0.00 | 1.00 |

The abbreviations S1–S3 refer to quays at the Sjursøya terminal while O1–O2 refer to quays at the Ormsund terminal. The distances in meters from these quays to the noise meter are as follows: 966 (S1), 910 (S2), 870 (S3), 504 (O1), and354 (O2). Distances associated with S1, S3, and O2 are used when calculating abatement costs (cf. Section 3.4), as these quays receive the largest container volumes in the period under consideration.

## 4.1. Empirical implementation

Note that the model in Eq. (6) can only be estimated using data for hours where containers are being loaded/unloaded (i.e., when the number of containers is non-zero in at least 1 of the 5 locations covered by the dataset) because log(0) is undefined. This leads to omission of many observations; i.e., only 1,251 observations are maintained in the dataset when estimating this model. From a statistical point of view this is a drawback, especially because observations that characterize the base sound level when there are no port activities are forgone. Inspired by Battese (1997), an alternative model specification that includes a structural shift dummy ($\alpha$) that is equal to 0 in hours when containers are being loaded/unloaded and 1 in hours with no container activities is also considered as a sensitivity test. This specification effectively exploits all observations in the sample.

$$\frac{L_{j,s}-120}{10}=\beta_0+\log\left(\beta_\alpha\alpha+\sum_{k=1}^{K}\left(\frac{y_{k,j,s}^{\beta_y}}{4\pi d_k^{\beta_d}}\right)\right)+\sum_{n=1}^{N}\beta_{z,n}z_{n,j,s}+\varepsilon_{j,s} \tag{15}$$

Models (6) and (15) are fitted using Nonlinear Least Squares as implemented in the econometrics software Stata. Table 2 reports the parameter estimates of the sound intensity function, which reveal that the model specifications in Eqs. (6), (15) produce close to identical results. The main exception relates to the southern wind (i.e., wind direction) dummy variable.

Table 2. Empirical results.

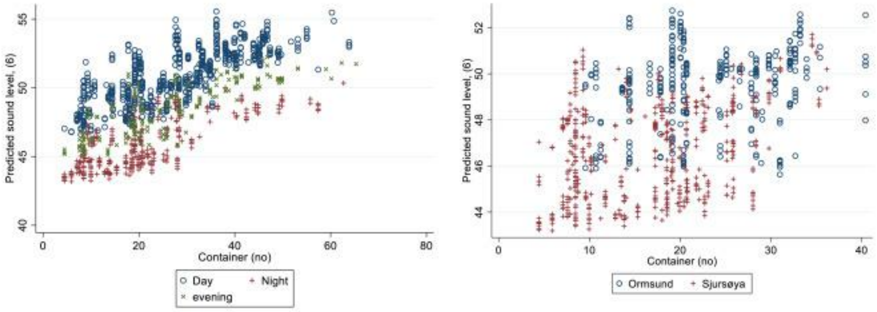
| **Variable** | **(6)** | **(15)** |
|---|---|---|
| Constant | −5.147*** | −5.207*** |
| | (0.196) | (0.192) |
| Containers (nr.) | 0.120** | 0.124** |
| | (0.050) | (0.050) |
| Distance (m.) | 0.499*** | 0.501*** |
| | (0.056) | (0.056) |
| Day (Dummy) | 0.346*** | 0.344*** |
| | (0.020) | (0.015) |
| Evening (Dummy) | 0.167*** | 0.184*** |
| | (0.027) | (0.020) |
| Temperature (°Celcius) | 0.009*** | 0.013*** |
| | (0.002) | (0.002) |
| Moisture (%) | −0.111** | −0.135*** |
| | (0.056) | (0.043) |
| Wind (m/s) | 0.045*** | 0.055*** |
| | (0.006) | (0.005) |
| Southern wind (Dummy) | 0.016 | 0.092*** |
| | (0.022) | (0.016) |
| $\alpha$ (Structual shift dummy) | | 0.003** |
| | | (0.001) |
| *N* | 1,251 | 2,141 |
| *Adj. R*$^2$ | 0.419 | 0.489 |

Standard errors in parentheses.

*p<0.10, **p<0.05, ***p<0.01.

Appendix B presents a scatterplot of the predicted logarithmic sound intensity level at the receiver resulting from both model specifications presented in Table 2. It finds that the results are robust, i.e., highly invariant to the model specification. The models have also been fitted with ship engine size as a contextual variable, which has negligible impact on the proceeding results. Other robustness checks include estimating the model with a time trend or month dummies and using alternative model specifications for contextual variables (i.e., both by omitting and adding a quadratic term for "moisture"[7]). Combined, these tests show that noise predictions are robust to changes in model specification. This suggests that the results of the emission model (i.e., the sound intensity function) is generic, and possibly that the fitted model could be applied to study noise emissions and costs in other container ports that are comparable to the port of Oslo. The finding that controlling for engine size has a negligible impact on the results could mean that emission model results are generalizable to container ports serving other types of ships than the port of Oslo. This can only be determined by further empirical investigation, which is beyond the scope of the current paper.

Fig. 4 presents how the predicted logarithmic sound intensity level at the receiver (i.e., at Ormøya) varies according to i) time of day (i.e., day, evening, night), ii) location, and iii) the port's overall container handling activities (i.e., the number of containers handled per hour, all quays taken into consideration). Note that this concerns hourly predicted sound intensity levels at the receiver and does not take penalties for sounds occurring in the evening or at night into account.



*A: Predicted hourly logarithmic sound intensity levels, by time of day*

*B: Predicted hourly sound intensity levels, by terminal (wo/simultaneous calls at both terminals)*

Fig. 4. Predicted hourly logarithmic sound intensity levels.

Fig. 4 shows that while the sound intensity level at the receiver increases in the port's overall container handling activities, it can also vary substantially for a given level of port activities because of contextual factors. Panel 4A shows that the sound level peaks during the day when the city is bustling with activities and declines in the evening and at night. Panel 4B – which ignores hours when there are joint container activities at the Sjursøya and Ormsund terminals – shows that container activities at Ormsund are more harmful to the inhabitants at Ormøya than corresponding activities at the Sjursøya terminal. The reason is that the distance from the sound meter at Ormøya to the Ormsund terminal is about half the distance from the meter to the Sjursøya terminal.

A comparison of sound levels at the receiver with and without port activities is made using Eq. (15) to calculate sound levels for reported container operations and for the counterfactual scenario where the container throughput is set to zero. A quadratic prediction plot of the two set of results is reported by Fig. 5, which suggest that port activities may increase the average sound level at the receiver by as much as 8 dB relative to the reference sound level.

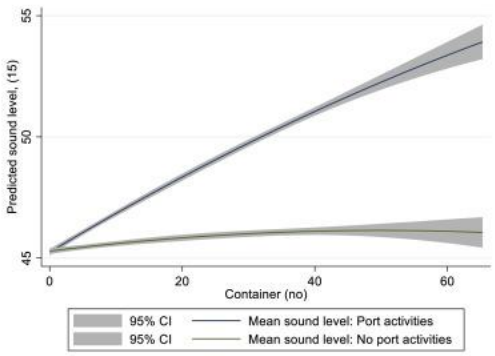


Fig. 5. Quadratic predicted hourly logarithmic sound intensity levels with and without port activities.

## 5. Results

In this section, the estimated models are used to analyze the social costs of container handling, as well as the potential for and costs of noise mitigation.

### 5.1. Marginal external costs of container handling

Fig. 6 presents the contributions of a marginal container to the hourly average sound level at the receiver. This calculation utilizes Eq. (11) to compute derivatives of Eq. (6) (i.e., the noise prediction model) for each individual hour contained in the dataset described in Section 4. Fig. 6 synthesizes these results in the form of line plots. To ensure that the figure is readable, results are only presented for the two quays that are most frequently in use in container handling operations in Oslo.

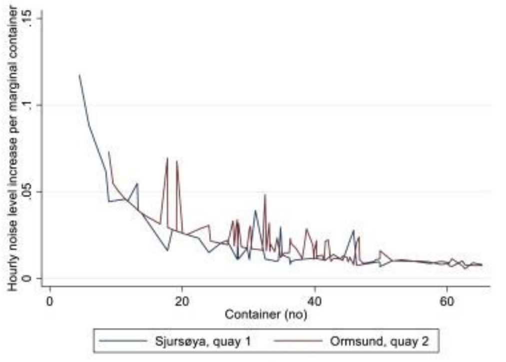


Fig. 6. Increase (ΔdB) in equivalent continuous sound level per hour due to a marginal container handled per hour, according to the port's hourly total container throughput.

Fig. 6 shows that the sound level increase per marginal container declines in the total number of containers being handled, which results because the sound level is measured on a logarithmic scale. At the same time, the number of people affected and the sound level they are exposed to are likely to increase with the number of containers handled. These opposing forces must be considered when determining the marginal environmental impacts of expanding port operations.

Marginal external costs are computed based on the marginal change in noise from an additional container, as visualized by Fig. 6. As Fig. 6 regards changes in hourly noise, these estimates (i.e., changes in hourly noise from a marginal increase in container handling) must first be multiplied with the corresponding changes in $L_{den}$ from the change in hourly noise – as shown by Eq. (9) – to estimate the impact of a marginal container on $L_{den}$. These estimates must in turn be multiplied with the damage cost function (which in this study is assumed to be linear; cf. Section 3.3) to estimate the economic value of changes in noise, i.e., the marginal external costs of container handling.

The derivatives of $L_{den}$ are calculated according to Eq. (10) using averages over all observations in the dataset to obtain *average* derivatives per hour and 24-h period. This contrasts with computing unique derivates of $L_{den}$ per day, which will lead to more variation. The long-run average of $L_{den}$ is here considered a more relevant metric for noise legislation than day-to-day variations.

Fig. 7 presents a fractional polynomial plot of predicted marginal external noise costs per person per year. While the average marginal costs per quay range from 0.25 (O2) to 0.57 (S1) NOK (i.e., (0.25/10) and (0.57/10) Euro), Fig. 7 shows that marginal costs per person are substantially higher at night than during the day and evening. Moreover, marginal costs are higher when the number of containers handled per hour is low, indicating economies of scale in sustainable port production.

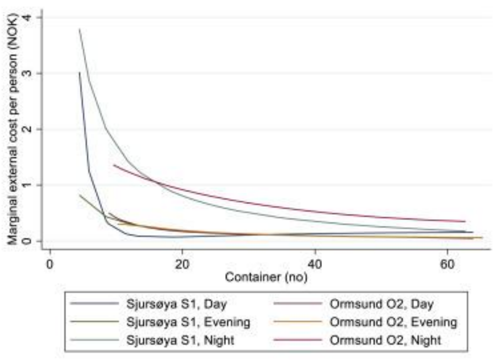


Fig. 7. Marginal external noise costs per person per year, according to the port's total throughput.

Fig. 7 provides an overview of marginal external costs per person per year using recommended damage costs from the Norwegian valuation study. That is, using a constant damage cost per decibel; cf. Section 3.3 for a discussion on linear and non-linear damage costs.

If one is willing to accept the use of a linear damage function, these estimates can be applied to predict marginal external noise costs by multiplying marginal costs per person by the number of persons affected by noise related to the port in question. An illustration for Oslo is provided: According to an external noise mapping (Heggøy, 2018), 4 houses were affected by average daily noise levels exceeding 55 dB due to activities of the container port of Oslo in 2014. An estimate of about 60 houses is further provided for the category 50–55 dB. The estimates reported by Heggøy (2018) are based on the Nordic Method for Industrial Noise using CadnaA and statistics about crane operations and other port activities. Overall, they suggest that disutility from container operations in Oslo is limited, a finding that may not be generalizable to other urban container ports.

Using the average number of inhabitants per house in Oslo (i.e., 1.97) mean marginal costs for Oslo range from 1.95 (O2) to 4.52 (S1) NOK for the 4 houses in the 55–59 dB category and between 31.2 (O2) and 73.32 (S1) NOK when considering all households facing noise levels above 50 dB. These are annual costs that must be divided by the number of days of port operation per year to obtain the marginal external noise costs per container. For example, assuming 325 days of port operations gives average costs ranging between 0.006 and 0.014 NOK per container for households in the 55–59 dB group and 0.096 and 0.223 NOK per container for households facing noise levels above 50 dB. For comparison, Rødseth et al.'s (2018) estimates of marginal external costs of nitrogen oxides ($NO_x$) emissions range between 40 and 60 NOK per container handled in Oslo.

## 5.2. Abatement costs

Next, abatement costs of noise regulation are considered. These are computed based on Eq. (14) using the recipe outlined in Section 3.4. The linear program in Eq. (14) is implemented in GAMS, and solved for different caps on $L_{den}$. The maximal number of containers that can be handled per day under the noise cap is compared to the maximal number of containers observed in the dataset (i.e., 982 containers handled per day). Deviations from the observed maximum are interpreted as abatement costs, measured in terms of forgone containers per day because of the noise regulation.

Using maximal capacity as a benchmark to compute forgone revenue can exaggerate current abatement costs as the port may not operate at full capacity. However, from the perspective of a long-run assessment – considering the potential for the port to expand its activities to cater increased demand for maritime transports – best practice is a reasonable reference for computing economic losses.

The total number of forgone containers per year can be found by multiplying the number of forgone containers daily with the number of days in which the port is in operation per year (here assumed to be 325 days). Forgone annual revenues can in turn be calculated using port fees per container. The average port charge of the main container ports in Norway in 2014, reported in Rødseth et al. (2018), is used to estimate forgone revenues per day and year. The latter is based on arbitrarily chosen number of days of operation and is only intended as an illustration.

Table 3 summarizes the estimated number of forgone containers and revenues due to noise regulation. The results suggest that the current regulation (i.e., $L_{den}$ less or equal to 55 dB) is slightly binding. Current abatement costs are estimated at 800 NOK per day or 270,000 NOK per year, which amounts to about 1 NOK per container (measured in TEU) handled by the port in 2014. With a binding noise cap, the prospects for port expansion seem limited under the current regulatory scheme. One option for the port could be to relocate its container activities to other facilities that are situated further away from the population. This option is already considered by the model framework as the container handling can be shifted from Ormsund to Sjursøya. The scope for locational shifts is, however, limited by the capacity of the Sjursøya terminal.

Table 3. Abatement costs of noise mitigation.

| **dB** | **51** | **52** | **53** | **54** | **55** |
|---|---|---|---|---|---|
| Max. output subject to noise constraint | 508 | 812 | 956 | 980 | 980 |
| Foregone containers (Per day) | 474 | 170 | 26 | 2 | 2 |
| Foregone revenue (kNOK) per day | 195.0 | 70.6 | 10.8 | 0.8 | 0.8 |
| Forgone annual revenue (kNOK) | 63,931 | 22,929 | 3,507 | 270 | 270 |

Table 3 showcases the nonlinearity of the dB measure: Reducing the noise cap by a few dBs can bring about substantial abatement costs. When the noise cap is lowered from 55 to 51 dB, the maximal allowable production is about half of the maximal current production, given the constraints of the current port production technology.

## 5.3. Environmental efficiency

Finally, the environmental performance of calls with loading/unloading of containers, including calls (i.e., time periods) where ships are jointly berthed in Ormsund and Sjursøya, is considered; cf. Section 3 for further elaboration on the structure of the dataset and the definition of a call. In total, 52 calls are recorded in the period under observation. Using the estimation approach outlined in Section 3.2, environmental efficiency scores for each of them are calculated based on averages of residuals per call from the model defined by Eq. (6). A histogram of the point estimates is provided by Fig. 8.

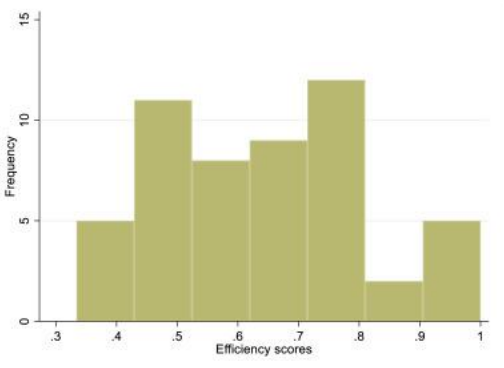


Fig. 8. Histogram of environmental efficiency score estimates.

The average efficiency score is 0.64, which means that the average call could reduce the sound intensity at the receiver by 36 percent without reducing container throughput. Fig. 8 showcases that efficiency scores are unevenly distributed over the interval 0.33 to 1, hence indicating a vast potential to reduce external costs by adopting best practices in noise mitigation during container handling.

## 6. Concluding remarks

While external costs are among the principal reasons for policy interventions in the transport sector, the economic importance of externalities caused by terminal operations remains largely unexplored. This paper extends the scope of Rødseth et al.’s (2018) study by analyzing the economics of noise pollution of container handling at a seaport. In line with Rødseth et al. (2018), marginal external costs of port operations are found to be higher in the case of low-density loading/unloading operations. This confirms Rødseth et al.‘s claim that Pigouvian port tariffs are regressive, i.e., favoring calls with large containers volumes. Moreover, this study finds that optimal noise pricing implies higher charges at night than during the day and evening. The relevance of time-of-day differentiation confirms the recent results of Swärdh and Genell (2020) on the marginal costs of road noise. While several contributions discuss marginal cost pricing of ports (see Acciaro, 2013 for a review), port charges accommodating time-of-day pricing of noise appear unexplored. More attention has been paid to congestion pricing (see e.g., Zheng et al., 2020), which has a different time profile than noise pollution.

Abbes (2007) considers complex estimation of marginal external costs as one of the major obstacles to marginal cost pricing of seaports. This paper showcases a simple and transparent framework that enables marginal cost pricing of noise pollution. Robustness tests indicate that noise estimates are invariant to changes in the model specification, which suggests that results from the port of Oslo could be generalized to other container ports. With suitable modification – e.g., regarding damage costs and the number of affected persons – the framework can be applied in transport cost-benefit analysis, which in Norway and elsewhere currently ignores external costs of terminal operations. In particular, the assumption of a linear damage function could be relaxed in subsequent studies.

Focusing on the case of Oslo, marginal noise costs are found to be insignificant compared to marginal air pollution costs (cf. Rødseth et al., 2018). Swärdh and Genell (2020) show that marginal noise costs depend on the number of individuals exposed, which in the case of the port of Oslo are few. Moreover, monetary damage cost estimates used in this study are solely based on valuation of noise disturbances. Extending the valuation to health outcomes – which remain to be implemented in the Norwegian valuation study – will increase the magnitude of marginal external costs. However, the conclusion that marginal noise costs are low in the case of Oslo is robust to the omission of health outcomes.

The abatement cost estimates exhibit nonlinearity in the noise metric, which means that reducing the noise cap by a few dBs can bring about substantial abatement costs. The case study indicates that the noise cap applicable to container handling in Oslo was binding in 2014. In 2016, the port of Oslo moved its container handling to a new terminal at Sjursøya. A key motivation was to enable expansion of port activities whilst obeying noise regulation.

Comparing the marginal external and abatement cost estimates – with the caveat that assumptions required to produce these estimates may have weaknesses, as discussed herein – the costs of noise regulation appear to outweigh its benefits in the case of Oslo. This may imply that current noise standards in Norway are not based on the cost-benefit principle. The model framework developed in this study can be utilized for further investigation to provide a sound knowledge base for port noise regulation.

Efficiency scores indicate a substantial variation in unobserved heterogeneity among calls. Using noise meter data, it cannot be ruled out that such variations relate to other factors than managerial efficiency of container handling, e.g., traffic conditions on adjacent roads. Regardless of cause, there seems to be a vast potential to mitigate noise by adopting best practices, either by taking noise reducing measures when handling cargo or to schedule handling when background noise conditions are more favorable. Research on contextual factors which can explain differences in environmental performance is a fruitful avenue for further research.

In addition to contributing to the transport literature, this paper also adds to the literature on environmental production analysis. While the latter is maturing, there is still a debate about the virtues of the existing production models and their alignment with physical laws. This paper makes several contributions to this debate. First, it broadens the scope of the environmental production analysis literature, focusing on nonmaterial rather than material pollutants. Second, an environmental production analysis framework that incorporates the basic principles of sound theory is proposed and used in an empirical application. Third, it discusses the use of environmental production models for estimating marginal external cost. While marginal external costs are considered important decision support e.g. in cost-benefit analysis, surprisingly few environmental productivity analyses emphasize them. Finally, while a substantial number of environmental production analysis studies estimate abatement costs, most rely on the shadow pricing technique (see e.g., Zhou et al., 2014 for a review). A drawback of this approach is that the abatement cost estimates are sensitive to the choice of distance function or direction vector. This paper maximizes production subject to a noise constraint, which ensures that the estimated abatement costs are unique. The proposed model incorporates the choice of location of production facilities, which is an important aspect of land use planning.

Noise is among the most important pollutants, and comprehensive noise mappings are undertaken every four years in Norway. However, most of the software and tools used for this purpose are not open access, and high user fees and costs can be a substantial barrier to noise assessments. This paper proposes a low-cost alternative which could help making noise assessments widely available. Comparison of the results of the environmental production analysis approach and standard methods for noise assessments, as well as the calibration of the proposed environmental production analysis method based on results from noise assessments, are both fruitful avenues for further research.

## Author statement

**Kenneth Løvold Rødseth**: Conceptualization, Methodology, Software, Formal analysis, Investigation, Visualization, Writing- Original Draft, Writing - Review & Editing, Funding acquisition.

See https://www.elsevier.com/authors/journal-authors/policies-and-ethics/credit-author-statement↗.

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## Appendix A.

Following Kuosmanen (2012), the sound intensity function can be estimated using Convex Nonparametric Least Squares. This approach assumes no functional form of the sound intensity function, but imposes the following axioms.

i) $f$ is monotonic increasing in $y$

ii) $f$ is globally concave

The Convex Nonparametric Least Squares estimator of Eq. (5) is defined as follows:

$$\begin{aligned}
&\min_{\gamma,\beta,\varepsilon} \sum_{j=1}^{J} \sum_{s=1}^{S} \varepsilon_{j,s}^2 \qquad (16)\\
&s.t.\\
&\frac{L_{j,s}-120}{10} = \beta_0 + \log_{10}(\gamma_{j,s}) + \sum_{n=1}^{N} \beta_{z,n} z_{n,j,s} + \varepsilon_{j,s}, \forall j, s\\
&\gamma_{j,s} = \delta_{j,s} + \beta_{y,j,s} \sum_{k=1}^{K} \left(\frac{y_{k,j,s}}{4\pi d_k^{\beta_d}}\right), \forall j, s\\
&\gamma_{j,s} \le \delta_{j',s'} + \beta_{y,j',s'} \sum_{k=1}^{K} \left(\frac{y_{k,j,s}}{4\pi d_k^{\beta_d}}\right), \forall j, j', s, s' \quad \text{(Concavity)}\\
&\beta_{y,j,s} \ge 0, \forall j, s \ \ \text{(Monotonicity)}\\
&\beta_d \ge 0
\end{aligned}$$

which is equivalent to the conventional Convex Nonparametric Least Squares model when $\beta_d$ is exogenous. Kuosmanen and Johnson (2010) explore the relationship between the Convex Nonparametric Least Squares estimator and the well-known Data Envelopment Analysis approach (Charnes et al., 1978) for efficiency analysis, and find that the latter can be understood as a special case of nonparametric least squares subject to shape constraints. Consequently, Eq. (16) may be modified to estimate a Data Envelopment Analysis model incorporating acoustic noise by constraining errors: $\varepsilon_{j,s} \ge 0, \forall j, s$.

## Appendix B.

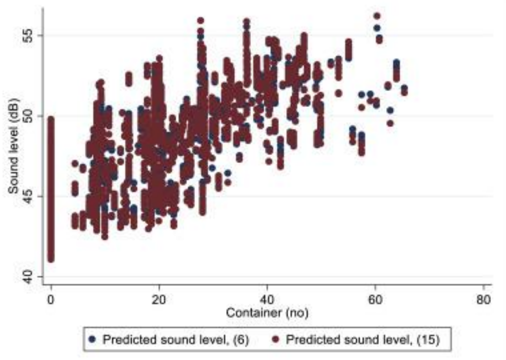

Fig. B.1. Comparing the two model specifications

## Data availability

Data will be made available on request.

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[1] https://www.eea.europa.eu/soer-2015/europe/noise ↗.

[2] See https://www.ecoports.com/publications/top-10-environmental-priorities-of-eu-ports-2020 ↗ (accessed 26.03.2021).

[3] Noise contours describe the size of the adjacent area where the average daily noise due to airport activities exceed a given threshold, e.g., 55 dB.

[4] This section is based on Sandberg and Ejsmont (2002).

[5] Noise can also be represented by *sound pressure*, which in our setting corresponds to a transformation of the (logarithmic) sound intensity level. Rødseth et al. (2017) find that basing the environmental production model on the sound intensity or pressure has no implications for the empirical results.

[6] Statistics Norway has granted access to the port statistic subject to a confidentiality clause.

[7] One referee noted that the negative sign of the parameter estimate of *moisture* in Table 2 is unexpected. Further investigation finds that the distribution of the moisture variable is highly left skewed. It is therefore likely that the statistical model places much weight on observations reporting high moisture. Moreover, the noise attenuation coefficient can be non-linear in moisture. The emphasis on observations with high moisture is thus a possible explanation for the negative parameter estimate. Robustness checks reveal that alternative model specifications for *moisture* lead to very similar predictions as the models presented in Table 2.