TØI report 1390/2015

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Institute of Transport Economics
Norwegian Centre for Transport Research

Production analysis in port economics: A critical review of modeling strategies and data management

TØI Report
1390/2015

Application of production analysis in port economics: A critical review of modeling strategies and data management

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Front page photo: Shutterstock

ISSN 0808-1190
ISBN 978-82-480-1151-4 Electronic version

Oslo, January 2015

Title: Application of production analysis in port economics: A critical review of modeling strategies and data management

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Date: 01.2015

TØI report: 1390/2015

Pages 63

ISBN Electronic: 978-82-480-1151-4

ISSN 0808-1190

Financed by: KS Bedrift
The Norwegian Coastal Administration
The Research Council of Norway

Project: 4077 - Examining the Social Costs of Port Operations

Quality manager: Halvor Schøyen

Key words: Analysis
Economics
Efficiency
Harbour
Port
Productivity

Summary:
This report contains the first output from the research project entitled EXPORT, which is financed by the Research Council of Norway, the Norwegian Coastal Administration, and KS Bedrift Havn. The report contains a critical review of the international literature using production analysis to ports. The report discusses modeling strategies and data management, and concludes by providing recommendations for the subsequent work on EXPORT.

Language of report: English

Tittel: Anvendelse av produksjonsanalyse innen havneøkonomi: En vurdering av modelleringsstrategier og databruk

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Dato: 01.2015

TØI rapport: 1390/2015

Sider 63

ISBN Elektronisk: 978-82-480-1151-4

ISSN 0808-1190

Finansieringskilde: KS Bedrift
Kystverket
Norges forskningsråd

Prosjekt: 4077 - Examining the Social Costs of Port Operations

Kvalitetsansvarlig: Halvor Schøyen

Emneord: Analyse
Effektivitet
Havn
Miljø
Produktivitet
Økonomi

Sammendrag:
Denne rapporten er skrevet forbindelse med gjennomføringen av prosjektet EXPORT, som finansieres av Forskningsrådet, Kystverket og KS Bedrift Havn. Rapportens gir en kritisk gjennomgang av den internasjonale faglitteraturens bruk av produksjonsanalyse innenfor havnesektoren. Rapporten diskuterer både modelleringsstrategier og databruk, og gir avslutningsvis anbefalinger for det videre arbeidet med EXPORT-prosjektet.

This report is available only in electronic version.

Rapporten utgis kun i elektronisk utgave.

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Preface

This report responds to task 1.1, but also addresses issues relevant to task 1.2, of Work Package 1 of the research project entitled "Examining the Social Costs of Port Operations", abbreviated EXPORT. This project is financed by the Research Council of Norway, the Norwegian Coastal Administration, and KS Bedrift Havn, and will be implemented in the period between 2014 and 2018.

The overall objective of the EXPORT project is to examine environmental-economic trade-offs in cargo handling in Norwegian ports. We consider microeconomic production analysis to be an appropriate tool for this purpose, in particular since a series of production models that include externalities have recently been developed. This report provides an overview of the previous research in port economics using production analysis. We comment on the strengths and shortcomings of this literature, and propose novel strategies for modelling port operations that are in line with the state-of-the art in production modeling. On the basis of our review and discussions, we propose data and modeling strategies for the EXPORT projects' subsequent empirical analyses.

EXPORT's project leader Kenneth Løvold Rødseth and Paal Brevik Wangsness (Institute of Transport Economics) have written the report. Halvor Schøyen (Buskerud and Vestfold University College) has been the quality manager. We are grateful to Thorkel Askildsen at the Norwegian Coastal Administration for providing helpful comments to the manuscript. Of course, the usual disclaimer applies.

Oslo, January 2015
Transportøkonomisk institutt

Gunnar Lindberg
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Content

Institute of Transport Economics
Norwegian Centre for Transport Research

Summary:

Production analysis in port economics: A critical review of modeling strategies and data management

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The main purpose of the report is to provide an overview of the previous research on port economics using production analysis. We comment on the strengths and shortcomings of this literature, and propose novel strategies for modelling port operations. On the basis of our review and discussions, we identify relevant data and modelling approaches for the EXPORT projects' empirical analyses.

This report responds to task 1.1 of Work Package 1 of the research project entitled "Examining the Social Costs of Port Operations" (EXPORT). The report is tailor-made for the researchers contributing to the EXPORT project, but will also be of interest to other researchers in the field of port economics and production analysis.

We find that most of the previous studies on port productivity and efficiency emphasize container terminals using either Data Envelopment Analysis (DEA) of Stochastic Frontier Analysis (SFA) to evaluate technical and scale efficiencies. The majority of studies treat stock input data, such as the number of cranes and tugs. We consider *flow variables* (e.g. the *use* of cranes) to be more relevant for Norwegian ports, especially when considering returns to scale. The reason is that previous studies have found that Norwegian ports exhibit low degrees of capacity utilization.

Externalities which are jointly produced with the cargo throughput is usually not considered by the port economics literature. There are to our knowledge only four relevant production analyses that consider bad outputs from port operations. The EXPORT project can consequentially be expected to contribute significantly to improving and extending this research area.

On the basis of our review on the port economics literature, and its applied data and methods, we identify the following issues that should be addressed by future research:

- Ports are multi-output producers and there may be economies of scope related to the handling of multiple cargo types. The majority of existing studies consider only one cargo type, namely containers.
- Cargo-handling inputs may be cargo-specific or common to all cargo types. This technology structure suggests that a multi-plant or network production model is appropriate for modelling port operations. The drawback of this approach is its extensive data requirement.
- Even for a given cargo-segment, it can make sense to separate port operations into different sub-units. Bichou (2011) argues that a container terminal is comprised of three sub-units; the quay, the yard, and the gate.
- The ports' objectives are guidelines for choosing appropriate function representations and thus efficiency measurements for ports. It is for example not

useful to consider profit efficiency if profit maximization is not considered a desirable objective by the port.

- Most externalities from port operations depend on the ports' activities. Examples include air pollution emissions and noise. Using stock input data to model the generation of externalities (e.g., by a production function approach) may thus provide biased estimates, because it is the use of the equipment, not the amount of equipment, that determines the emissions. It is also a problem that the port economics literature generally applies production analysis techniques intended for real-valued inputs to integer-valued inputs such as the number of cranes and tugs.
- Most studies define returns to scale of port operations in terms of port expansions (e.g., expansion of the port area and equipment stock). In Norway it may be more important to consider expansions of capacity utilization rather than physical expansions of the port infrastructure because of the ports' apparent overcapacities. That is, it may be more sensible to evaluate returns to density (Caves et al., 1984) rather than returns to scale for Norwegian ports.
- Externalities such as noise and air pollution emissions are among the most important externalities caused by port operations, and they have properties that make them suitable for modelling by traditional production analysis. However, emissions to sea and soil are important too, but they are of a more stochastic nature. Hence, traditional production modelling may not be suitable for characterizing these types of joint production. Instead, alternative models developed by the agricultural economics literature on production risk may be appropriate.

Taking into account the state-of-the art in production modelling as well as the available data for Norwegian ports, we close the report by discussing the empirical and methodological aims of the EXPORT project within the field of traditional and environmental port economics. Focusing on environmental port economics, we propose four modelling approaches that can be considered in the proceeding phases of the project:

- Modelling turbidity as a function of the number of ships leaving and entering the port
- Air pollution emissions from ships as a function of the time spent at berth
- Noise and air pollution emissions from land-based port operations
- A risk assessment for emissions to sea and soil

Sammendrag:

Produksjonsanalyse innen havneøkonomi: En vurdering av modelleringsstrategier og databruk

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Forfattere: Kenneth Løvold Rødseth og Paal Brevik Wangsness
Oslo 2015 63 sider

Hovedformålet med rapporten er å gi en oversikt over forskningen som anvender produksjonsanalyse innen havneøkonomi. Vi vil poengtere styrkene og svakhetene til den eksisterende litteraturen, og foreslå nye strategier for å modellere havneoperasjoner. Vår gjennomgang og diskusjon er et ledd i å identifisere relevante data og modelleringsstrategier til EXPORT-prosjektets empiriske analyser.

Denne rapporten svarer til deloppgave 1.1 av Arbeidspakke 1 knyttet til forskningsprosjektet "Examining the Social Costs of Port Operations" (EXPORT). Rapporten er skreddersydd for forskerne som bidrar til EXPORT-prosjektet, men vil også være av interesse for andre forskere innen havneøkonomi og produksjonsanalyse.

Vår gjennomgang avdekker at de fleste tidligere studier om havneproduktivitet- og effektivitet fokuserer på containerterminaler og benytter enten Data Envelopment Analysis (DEA) av Stochastic Frontier Analysis (SFA) til å vurdere teknisk effektivitet og skalaeffektivitet. Flertallet av studiene benytter kapitalbeholdnings-data, for eksempel antall kraner og slepebåter. Vi anser strømvariabler (f.eks. *bruken* av kran) til å være mere relevante for norske havner, spesielt i en analyse av skalafordeler.

Eksternaliteter som oppstår i forbindelse med godsgjennomstrømmingen i havner er vanligvis ikke behandlet i produksjonsanalyselitteraturen om havneøkonomi. Det er så vidt vi vet bare fire relevante produksjonsanalyser som vurderer negative eksterne virkninger fra havnevirksomheten. EKSPORT-prosjektet kan dermed forventes å bidra betydelig til å utvide og berike dette forskningsområdet.

På bakgrunn av vår gjennomgang av den havneøkonomiske litteraturen, og dens anvendte data og metoder, identifiserer vi følgende problemstillinger som vi mener bør adresseres i fremtidig forskning:

- Havner håndterer multiple godsslag, og vi anser derfor at det kan være samdriftsfordeler knyttet til håndtering av flere typer gods. Flertallet av eksisterende studier vurdere bare én type last, nemlig containere.
- Innsatsfaktorer til lasting og lossing kan være gods-spesifikke eller felles for alle typer gods. Denne teknologistrukturen antyder at en nettverksproduksjonsmodell er egnet for modellering av havnevirksomhet. Ulempen med denne tilnærmingen er at databehovet er omfattende.
- Uavhengig av godstype kan det være fornuftig å skille havnedriften i forskjellige deloperasjoner. Bichou (2011) argumenterer for at operasjonene

innen en container-terminal kan plasseres i tre hovedgrupper; kaikanten, lager/oppstillingsområde og havneporten.

- Havnens uttalte målsetninger danner retningslinjer for hva som er en hensiktsmessig funksjonsrepresentasjon og dermed effektivitetsmål for havner. Det er for eksempel ikke hensiktsmessig å vurdere profitteffektivitet hvis profittmaksimering ikke er en overordnet målsetning for havnen.

- Eksternaliteter ved havneoperasjoner avhenger av havnas aktiviteter. Eksempler på dette er luftforurensning og støy. Dersom man bruker beholdningsdata til å modellere eksterne virkninger (for eksempel, ved en produktfunksjonsmetode) kan man derfor risikere å lage forventningsskjeve estimater. Dette er fordi det er *bruken* av utstyret, og ikke mengden av utstyr, som bestemmer utslippene. Det er også et potensielt problem at den havneøkonomiske litteraturen generelt bruker produksjonsanalyseteknikker beregnet på innsatsfaktorer definert ved reelle tall, ettersom en rekke av innsatsfaktorene tydelig tar heltallsverdier (f.eks. antall kraner og slepebåter).

- De fleste internasjonale studier definerer skalafordeler av havnevirksomheten ut fra størrelsen på havnas kapitalbeholdning (f.eks. havneområdet og maskinparken). I Norge kan det være viktigere å vurdere utvidelser av kapasitetsutnyttelse i stedet for fysiske utvidelser av havneinfrastruktur. Det vil si, det kan være mer hensiktsmessig å evaluere tetthetsfordeler (Caves et al., 1984) i stedet for skalafordeler for norsk havner.

- Støy og luftforurensing er blant de viktigste eksternalitetene fra havnevirksomheten. Produksjonsanalysen er egnet til å modellere slike eksternaliteter. På den andre siden har vi eksternaliteter som utslipp til jord og sjø som også er viktige, men som er preget av å være av en mer stokastisk art. Tradisjonell produksjonsanalyse er dermed mindre egnet. I stedet kan alternative modeller for produksjonsrisiko, utviklet innenfor litteraturen om landbruksøkonomi, være anvendelige til å modellere disse eksternalitetene.

Etter å ta hensyn til forskningsfronten innen produksjonsmodellering og å kartlegge tilgjengelig data for norske havner, avsluttes rapporten med en diskusjon rundt de empiriske og metodiske mål for EXPORT-prosjektet innenfor både tradisjonell havneøkonomisk forskning og miljørettet havneøkonomisk forskning. Med tanke på prosjektets miljøøkonomiske fokus, foreslår vi fire modelleringstilnærminger som kan vurderes i de påfølgende fasene av prosjektet:

- Modellering av oppvirvlet, forurenset sjøbunn som en funksjon av antall skip som anløper havnen
- Luftforurensning fra skip som en funksjon av tiden brukt ved kai
- Støy og luftforurensning fra landbasert havnevirksomhet
- En risikovurdering av utslipp til sjø og jord

1 Introduction

This report responds to task 1.1, but also addresses issues relevant to task 1.2, of Work Package 1 of the research project entitled "Examining the Social Costs of Port Operations", abbreviated EXPORT. The report is tailor-made for the researchers contributing to the EXPORT project, but will also be of interest to other researchers in the field of port economics and production analysis[1]. Because researchers experienced in the field of production analysis are our target group, we will not go into details on production theory and modelling. For further details on production analysis and its applications, see Färe and Primont (1995) and Coelli et al. (1998).

The main purpose of the report is to provide an overview of the previous research within relevant[2] areas of the port economics literature. We will also comment on shortcomings of the existing port economics literature, and will propose novel strategies for modelling port operations using production analysis. Based on our review and discussions, we will identify relevant data for EXPORT's empirical analyses.

This report is structured as follows: In Section 2, we provide an overview of the EXPORT project in order to motivate our literature and data reviews. Section 3 provides a detailed description of port operations, and the inputs and outputs therein. Section 4 provides a detailed literature review on port economics, while Section 5 takes up additional issues on modelling port operations using production analysis. Section 6 presents an overview of the available data, while Section 7 discusses the main findings. Section 8 provides guidelines for data collection and microeconomic modelling of port operations.

[1] Production analysis is also sometimes referred to as productivity and efficiency analysis, and the two terms will be used interchangeably throughout. However, it is the authors' opinion that production analysis is a more general term than productivity and efficiency analysis, because the former also covers e.g. elasticities of scale and substitution, in additional to efficiency measurement.

[2] By relevant we mean literature and data that can contribute to the EXPORT project's analysis of private and external costs of port operations in Norway.

2 Background – The EXPORT project at a glance

One of the Norwegian government's main strategies for freight-transport, as outlined in its National Transport Plan (NTP), is to ensure that the future growth in long-distance freight transport takes place by maritime- or rail transport. Maritime transport's main advantages compared to e.g. road transport are thought to be i) lower infrastructure requirements, ii) higher energy efficiency, and iii) lower external costs, especially since a large share of the overall transport takes place at sea and, hence, far away from densely populated areas.

The maritime logistics chain involves the sea transport leg, loading and unloading in ports, and hinterland shipments. For each stage, new transport costs – internal and external – are added. Together, they make up the total costs of maritime freight transport, which, in turn, are key determinants of maritime transport's economic and environmental competitiveness.

Ports are vital components in the maritime logistics chain. International studies have pointed to the importance of ports' cost efficiencies and exploitation of economies of scale and scope for domestic competitiveness and economic growth; cf. Tovar et al. (2007). Comparable assessments for Norway are few (Lea and Lindjord 1996; Schøyen and Odeck 2013), and little information about cost reductions by better exploitation of the current port infrastructure – in particular by handling greater and more diversified freight volumes – is available.

While the (private) economic benefits of more efficient cargo handling in ports have been treated by the international literature (cf. Section 4), less attention has been devoted to the external costs of port operations. Such estimates provide important guidelines to policy decisions in the transport sector (Maibach et al., 2008). TØI did recently complete a pilot project on external costs of maritime transport, which concluded that proper estimates of the marginal external costs of port operations are lacking (Rødseth and Killi, 2014). Externalities related to ships are much better understood.

A narrow focus on ship externalities may neglect a large share of the full external costs of maritime transport. Ports are often located in densely populated areas and port operations are associated with manifold negative externalities such as noise, atmospheric pollutants, and accidental spillages of e.g. oil and hydrocarbons (Alderton, 2005).

The overall objective of the EXPORT project is to examine environmental-economic trade-offs in cargo handling in Norwegian ports. The expected outcomes of the project are:

1. New knowledge about the optimal (efficient) exploitation of the current port infrastructure in Norway, and how it contributes to lowering user costs and increasing the attractiveness of maritime transport. We consider this information highly relevant for policy makers and stakeholders in the Norwegian port sector.

2. New knowledge about marginal external cost estimations for ports. This information is of interest to the scientific community, policy makers, and environmentally conscious producers and transport providers.
3. Policy recommendations for maritime transport in general and the port sector in particular. This information is particularly interesting to policy makers and public administrators.

3 Port operations

The overall goal of this report is to shed light on how we can model port operations using microeconomic production analysis, and thus to identify which data should be collected for this purpose. We believe that the best point of departure for this task is to provide a description of port operations, before presenting a review of the port economics (production analysis) literature. We believe that the quality of any port operations model can be judged by the degree to which it reproduces the characteristics of port operations that are described in this section.

3.1 A general overview of port operations

We will now provide a general overview of port operations. First, we describe the different stages that port operations broadly can be classified into. Thereafter we provide a general overview of the different cargo types being handled by the port sector, emphasizing the inputs that the cargo handling requires.

3.1.1 Different stages in port operations

Jara-Diaz et al. (2006, p. 67) state that "what is known as port operations really encompass a large number of smaller operations, most of which form a successive links of a chain in which the weakest link is the one that determines the strength of the chain as a whole." They propose to separate port operations into three stages: ship-oriented services, cargo-oriented services, and inter-modal connections. Jara-Diaz et al. (2006) consider ports to be multi-output producers, handling a variety of cargo types.

Bichou (2011) considers only one cargo type, namely containers. He argues that the container terminal production is best viewed as a network of interrelated sub-processes and operating sites, where the performance and capacity of one site is a binding constraint for the performance of another site. In the words of Bichou (2011, p. 7), "modern container-terminal systems are designed and operated in terms of three main operating sites; the quay, the yard, and the gate."

A recent discussion on status and trends within transport operations in container terminals can also be found in Carlo et al. (2014). This article provides illustrative figures for both terminal operations and important inputs. These are reproduced by Figures 1, 2 and 3. Note that Figure 1 adds transfer vehicles to Bichou's (2011) three operating stages (the quay, the yard, the gate) for container terminals.

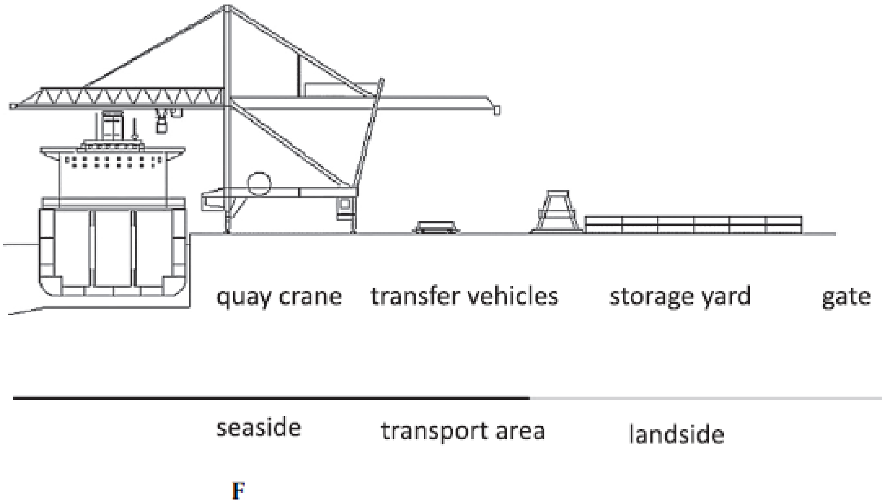

Figure 1: Container terminal main areas. From Carlo et al. (2014)

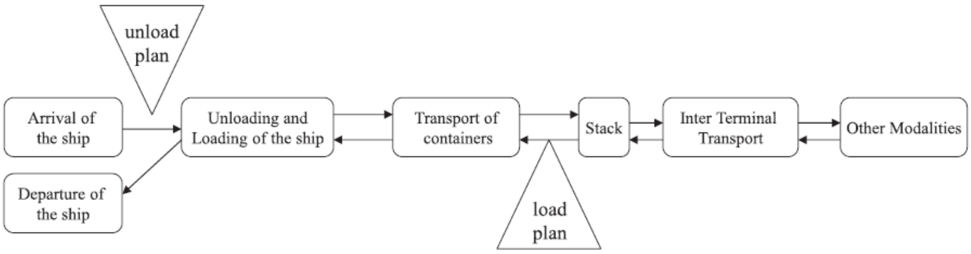

Figure 2: Loading and unloading processes at container terminals. From Carlo et al. (2014)

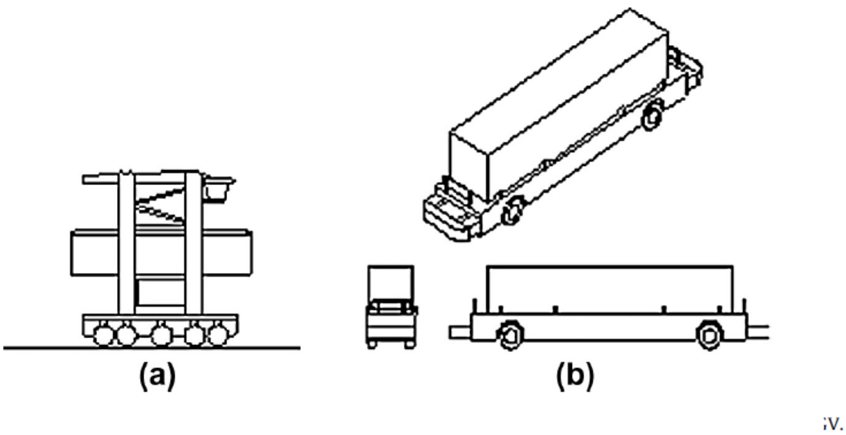

Figure 3: Two of the most common transfer vehicles[3] at container terminals; a) straddle carrier, b) Automated Guided Vehicle. From Carlo et al. (2014)

[3] Note that reach stackers are more common for Norwegian container terminals. The above illustration is, however, adopted from Carlos et al. (2014), who emphasize international trends.

3.1.2 Different cargo types and their input requirements

Having identified the different stages of port operations we will now turn to the ports' inputs and outputs. Jara-Diaz et al. (2006) provide a detailed description of the characteristics of port production, which we will lean on in the following presentation.

Jara-Diaz et al. (2006) argue that ships that are more specialized have induced more efficient port terminals and cargo-handling equipment. Because of the standardization process, the costs of port operations have become highly dependent on the cargo type under consideration. Containers, semi-trailers, and pallets are the most widely used forms of standardized loading units for maritime transport.

The overall cargo can broadly be categorized into (Jara-Diaz et al., 2006):

i) liquid bulks (oil and derivatives, liquid gases, edible oils)
ii) dry bulk (cereals, minerals, cement clinker etc.)
iii) general cargo in containers and carried on container ships
iv) general cargo in semi-trailers and containers, transported on Roll-on Roll-off (RoRo) ships
v) general non-containerized cargo.

Liquid bulk: The loading and unloading of liquid bulk is done using pipes running between tanks on shore and the ship. This type of loading/unloading requires little other inputs than the pipe equipment.

Dry bulk: There are different technologies available for handling dry bulk that broadly can be divided in two categories; specialized facilities and multipurpose facilities. Examples of specialized facilities include pneumatic loaders for cereals and conveyer belts for minerals, both of which rely on a direct connection between the cargo storage site and the ship. This type of cargo handling is much less labor intensive than multipurpose facilities, e.g. multipurpose cranes used for loading and unloading cereals and clinker, as workers have to pile up the bulk in the ship's holds in the latter case.

Containers (Container ships): The handling of containers requires specific facilities: port terminals with large storage spaces, gantry cranes for loading and unloading the container to the ship[4], and equipment for moving the containers within the terminal and for loading them on to the modes of land transport (Jara-Diaz et al., 2006)[5]. Another option for container handling is to transport them to the shipside on a rolling platform using tractors or mobile platforms.

Containers (RoRo ships): There are two approaches to container transport on Roll-on Roll-off ships. In one approach, the container is placed on a platform ("mafi-trailer") that is towed onto the ship. In the other, trucks are driven onto the ship.

General cargo: General non-containerized cargo takes different forms, e.g., rolls of paper, pallets, and cars. For such cargo, handling requires medium-sized cranes or forklifts through side ports. Forklift trucks are required to move the cargo while on shore. If the cargo is transported as individual units, specific fittings are required for cranes and forklift trucks. The reason is that the cargo is fragile, and specialized labor is consequentially required for these operations. Cargo like wood and iron can be

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[4] Alternatively, the cargo handling equipment (for several cargo types) can be mounted on the ship ("geared vessels"), as is also the case for container ships calling smaller, Norwegian ports.

[5] Note that the price of land can play an influential role for the height to which containers are stacked (Jara-Diaz et al., 2006).

transported by the pre-slung system, in which units are put together in bundles or batches.

3.2 A classification of inputs in port operations

Jara-Diaz et al. (2006) classify inputs as *specialized* or *common*, i.e., inputs are specific to cargo types or used for all cargo types. There are also inputs which are applicable to multiple cargo types, but not to all cargo types. We dub them semi-common inputs.

3.2.1 Common inputs

The degree of input specialization is positively correlated with the volumes of cargo being handled. However, even in large ports with highly specialized terminals, there are also inputs that are common to all cargo types. Typical examples are (Jara-Diaz et al., 2006)[6]:

- Lighthouses and shipping services
- Breakwaters
- Road networks
- Buildings
- Infrastructure
- Mechanical equipment and loading/unloading equipment management personnel
- Cargo handling personnel
- Inspection, customs, and port security services

3.2.1 Semi-common inputs

Some inputs are used for multiple cargo types, but not for all cargo types:

- General cargo docks are used for loading and unloading pallets and loose or pre-slung cargo. Here, stevedores, cranes, and the landside are common inputs.
- Tractors and platforms are used for most road traffic, and in some ports they are also used for moving containers on the dockside before they are loaded/unloaded by crane.

3.2.1 Specialized inputs

Specialized inputs include among others:

- Cold storage facilities for perishable goods
- Specialized container handling inputs:
  - o Berths in container terminals are cargo specific, and depend on the draught and length needed by the container ship
  - o Container handling requires spacious and dedicated areas close to the docks.
  - o The cranes for container handling are specialized cranes (normally gantry cranes)
  - o The mechanical equipment for handling and dispatching containers on land is specialized
- Dry bulk is handled using special facilities (e.g., specific docks, surface infrastructures, mechanical equipment) when large volumes are involved.
- Liquid bulk and several dry bulk commodities (e.g., powder, pellets, and granulates) require shore side tanks and pipelines

[6] Note that the quay front may be a common input.

4 Modeling port operations – a literature review

We will now review the literature on port economics, with emphasis on studies applying microeconomic production analysis. This section summarizes common approaches to port modeling and data use, while detailed information about the articles that we have reviewed can be found in the Appendix.

We classify the literature into two main categories; port economics with and without bad outputs (externalities). The literature that omits bad outputs is further classified into

i) terminal or single-output studies
ii) multi-output studies
iii) multi-plant and network technologies.

4.1 Port economics – without bad outputs

In their comprehensive review article Pallis et al. (2011) identify seven broad categories in which the literature on port economics could be placed:

i) terminal studies
ii) ports in transport and supply chains
iii) port governance
iv) port planning and development
v) port policy and regulation
vi) port competition and competitiveness
vii) spatial analysis of seaports

They identified 395 relevant articles from 51 different journals in the period 1997 to 2008.

4.1.1 Terminal studies: emphasis on one cargo type

This report focuses on productivity and efficiency of ports. In terms of the classification by Pallis et al. (2011), such studies generally belong to the category *Terminal Studies,* which include 40 articles from 1997 to 2008. Although the literature is growing, this is still a modest volume compared to efficiency and productivity studies carried out in other sectors, e.g. for railways, airports, electricity, and agriculture. It is also a relatively young research area. Although there exists earlier studies on aspects of efficiency and productivity in ports, Gonzalez and Trujillo (2009) and Cullinane and Wang (2006) both suggest that the first study advocating the use of production analysis techniques to ports was Roll and Hayouth (1993). However, this study is mainly theoretical, applying hypothetical data.

In addition to the review provided by Pallis et al (2011), Gonzalez and Trujillo (2009) provide a comprehensive overview of empirical studies on port efficiency up to 2009.

Productivity and efficiency analyses for ports published until 2009 are appropriately covered by these publications, and we will consequently build on them when covering scientific studies published before 2009. We will also provide an additional review on terminal studies published after 2009. Hence, we divide this section into two subsections; Until 2009 and After 2009.

4.1.1.1 Until 2009

In this subsection we give an overview of the methodologies and approaches, research objectives, input and output variables, and data sources that were most commonly used by terminal studies published before 2010.

Two methods dominate the port efficiency literature; Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA). Most studies using DEA and SFA estimate distance functions or production functions, but some SFA studies also estimate cost functions. Until 2009, the use of DEA and SFA were evenly distributed, indicating that there has not been established any consensus on which approach better reflects the port technology (Gonzalez and Trujillo, 2009). Cullinane et al (2006) compare the DEA and SFA methods, analyzing the technical efficiencies of 57 container terminals (in 28 ports). They conclude that even though the efficiency estimates vary with the different methods, they are highly correlated. The ports end up with similar rankings irrespective of the choice of method.

Gonzalez and Trujillo (2009) acknowledge that the literature on port efficiency and productivity takes up a broad range of topics on port performance. Among the most important are;

i) The effects of private ownership (e.g., Liu, 1995; Cullinane et al., 2002; Tongzong and Heng, 2005)
ii) Port size (e.g. Martinez-Budria, 1999[7]; Notteboom et al., 2000; Tongzon 2001; Cullinane et al., 2006, Wang and Cullinane, 2006)
iii) Port reforms (e.g. Estache et al. 2002; 2004; Barros, 2003; Gonzalez and Trujillo, 2008).

In their review article, Gonzalez and Trujillo (2009) find that, in spite of the recognition of ports as multi-output producers, most studies do not capture this characteristic when analyzing port efficiency. It is common to limit the studies to container terminals, with the main output being annual Twenty-foot Equivalent Unit (TEU) throughput, i.e., a quantitative output measure. Note, however, that a few studies consider the ports' annual revenues instead of the quantitative output measure (e.g., Liu 1995; Cullinane and Song, 2003; Martinez-Budria, et al. 1999). Some studies even apply both types of variables as outputs. One example is Barros (2003), who defines the number of ships, movement of freight, gross tonnage, market share, break bulk cargo, containerized cargo, roll-on/roll-off traffic, dry bulk, liquid bulk, and net income as outputs. Barros (2003) is recognized as the study with the highest number of outputs in Gonzalez and Trujillo's (2009) overview. Bonilla et al. (2004) include dry bulk, liquid bulk and general break-bulk in their analysis.

[7] Another interesting quality of this study is that the authors divide the ports into high- medium og low complexity ports, where they through the application of DEA conclude that the ports of high complexity are associated with higher efficiency than the other groups. The acknowledgement of the varying complexity of ports is of particular interest to the EXPORT-project. We seek to avoid comparing heterogeneous production units, and are therefore considering estimating separate technologies for different sub-groups of ports.

However, they incorporate a single input – infrastructure endowment – because they found that most input variables were highly correlated.

Gonzalez and Trujillo (2009) find that there is both a lack of consensus on what the relevant input variables for modelling cargo handling in ports are, and a lack of relevant data. Some studies apply capital inputs, some apply labor inputs, while some apply both. Capital inputs have both been represented by the value of capital, and by physical quantities (e.g. the length of docks, terminal surface area, and number of cranes)[8]. For labor inputs, some studies consider the value of labor (i.e., total salaries), while others use physical labor input (i.e., number of employees). Some studies have also included intermediate inputs like energy and consumption expenses (e.g. Martinez-Budria, 1999). Studies estimating cost functions (e.g. Coto-Millan, et al. 2000; Diaz, 2003) require price data. The labor price has commonly been obtained by dividing labor expenses on the number of employees, while the capital price has been obtained by a range of different methods involving dividing monetary values by physical capital assets.

The Containerization International Yearbook is a popular source for the capital stock data. Otherwise, or for other data, the studies have commonly obtained data directly from the ports (e.g., by surveys or from their annual reports).

4.1.1.2 After 2009

Several recent studies have assessed productivity change using DEA to estimate the Malmquist index[9], the most recent study being Song et al (2014) on Chinese ports. Other examples include Yuen et al. (2013) and Cheon et al. (2010).

Cheon et al. (2010) use DEA to a relatively large data set comprising 98 large container ports worldwide, observed in 1991 and 2004. We note that both Cheon et al's paper and other papers on international comparisons of ports (e.g., Schøyen and Odeck, 2013) construct a single DEA-technology based on their dataset. This is at odds with the general best-practice in the productivity and efficiency analysis literature, in which group-frontiers (country-wise) frontiers are usually constructed when international comparisons are concerned (see e.g., O'Donnell, Rao, and Battese (2008)). The group-frontier approach recognizes that different countries may differ in terms of operating environment for ports, e.g. due to regulations.

Among Cheon et al.'s (2010) most interesting contributions is their treatment on how different port practices may contribute to productivity growth. They decompose the overall productivity change (i.e. the Malmquist index) into technical change, pure efficiency change, and scale efficiency change, and identify (but not estimate the effect of) the following factors which are expected to play a role in determining the magnitudes of the three components:

[8] Note that the input quantity variables (e.g., the number of cranes and tugs) are stock variables. In economics, stock variables are usually considered to be quasifixed, i.e., they are unchangeable in the short run.

[9] The Malmquist index was originally proposed as a theoretical index by Sven Malmquist (1953), and was popularized as an empirical index by Färe et al. (1994). It has become one of the most popular tools for the evaluation of total factor productivity growth.

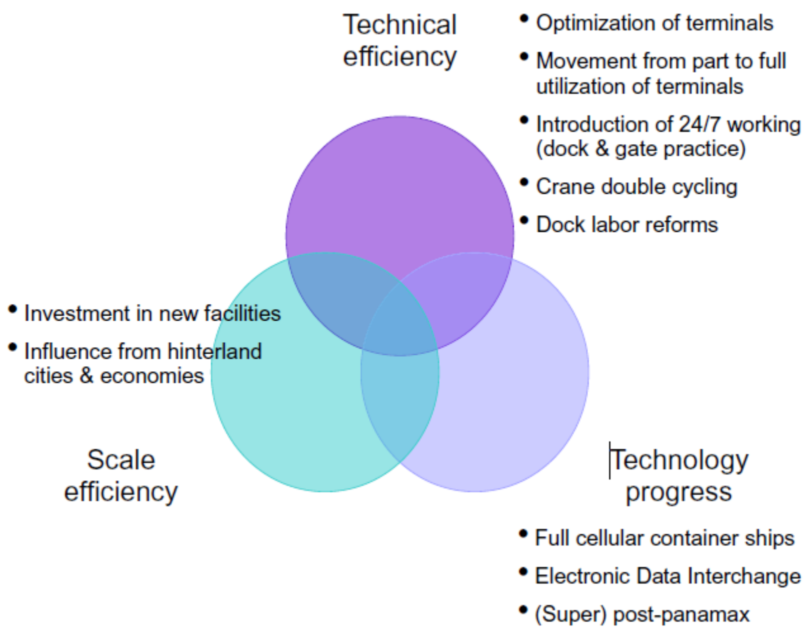

Figure 4: Examples of port practices for sources of efficiency gains. From Cheon et al. (2010)

The papers by Song et al (2014), Yuen et al. (2013) and Cheon et al. (2010) all consider container throughput as the single output variable. The same goes for Cullinane and Wang (2010), Alejandro and César (2009), Schøyen and Odeck (2013), and Munisamy and Singh (2011).

We conclude that the articles published after 2009 follow many of the same patterns as described by Gonzalez and Trujillo (2009). It is still common to use either SFA or DEA, but DEA now appears to be slightly more popular than SFA (Schøyen and Odeck, 2013). It is still common to analyse container terminals treating container throughput as the only output. Inputs such as quay length, terminal area, number of cranes (different types of cranes) are still dominating, and the Containerization International Yearbook is still one of the most important data sources.

While most of the recent studies focus solely on container throughput, there are also some recent studies that perceive ports as multi-output producers. Barros (2012a; 2012b) does for example include dry bulk and liquid bulk among the ports' outputs, in addition to container throughput. Simoes et al. (2010) and Simoes and Marques (2010a; 2010b) include passengers in addition to cargo. We note that the two latter studies use operating expenditure (OPEX) and capital expenditure (CAPEX) as input variables, instead of physical units such as cranes. These studies are largely dependent on collection primary data from the ports.

4.1.1.3 Summarizing the literature on port economics (terminal studies)

The following table gives a stylized summary of the most common input and output variables in studies on port efficiency using DEA or SFA.

Table 1: Inputs and outputs variables commonly used in the terminal studies literature

		Container terminals	Broader set of outputs
Output variables	Physical	Container throughput	Dry bulk cargo (tons), liquid bulk cargo (tons), containers (TEU) and passengers (number)
	Monetary	Annual revenue	
Input variables	Physical	Terminal length (m), Terminal area (ha), Quayside gantry cranes (number), Yard gantry cranes (number) and Straddle carrier (number)	Quay length (m), employees (number), cranes (number)
	Monetary	Salary payments and Net value of fixed capital	Operating Expenditure (OPEX) and Capital Expenditure (CAPEX)

4.1.2 Scale, scope and multi-output production

The ways in which economic activities are organized influence production costs and consequently play a key role in determining competitiveness. This issue was pioneered by Baumol, Panzar, and Willig in a series of publications (e.g. Baumol, Panzar, and Willig (1982)). According to their research, the key concepts for understanding industry structures and competitiveness are economies of scale and scope. The concept of economies of scale refers to the possibility to reduce costs by increasing the scale of operations (usually at the expense of the competition in the particular sector under consideration). The concept of economies of scope refers to reductions in operating costs that stem from the simultaneous production of multiple outputs. As a general case, the economic benefits arise from the sharing or joint utilization of inputs or assets. The concepts of economies of scale and scope have been identified as key determinants of ports' operating costs (e.g., Tovar et al. (2007)).

4.1.2.1 Economies of scale and scope in the port sector

Several of the studies reviewed in Section 4.1.1 address exploitation of scale economies by examining scale inefficiency (deviation from constant returns to scale). This is often done by comparing the DEA model under variable returns to scale (Banker et al, 1984) to the DEA model under constant returns to scale (Charles et al, 1978). An example is Cullinane et al. (2006), who implement the two models using a dataset that comprises 57 terminals. Of the overall sample, 13 exhibit constant returns to scale, 10 exhibit increasing returns to scale, and 34 exhibit decreasing returns to scale. Cullinane et al.'s results suggest a relationship between port size and returns to scale, as large ports are found exhibiting decreasing returns to scale while small ports exhibit increasing returns to scale. Similar approaches and results are also reported by Simoes and Marques (2010a; 2010b) and Munisamy and Singh (2011). The only comparable study for Norway (Schøyen and Odeck, 2013) suggests that scale economies are not fully exploited by the Norwegian container ports.

Neither of the studies mentioned here or in Section 4.1.1 examine economies of scope. In their review on scale and scope economies in the port sector, Tovar et al. (2007) conclude that the literature on economies of scope in port operations is scarce.

We note that if there are economies of scope in port operations, not considering them could lead to erroneous results. Recall that economies of scope imply that costs are higher for stand-alone production (i.e., for a single cargo type) than if multiple cargo types are handled jointly. One of the best-known reasons for economies of scope is sharing of inputs among multiple outputs; see Panzar and Willig (1981). Intuitively, neglecting shared inputs leads to "double-counting" of costs if separate cost functions are estimated for each cargo type (cf. the terminals studies in Section 4.1.1). Jara-Diaz et al (2006) have also shown that combining different cargo types into one output[10] will lead to the erroneous conclusion that ports exhibit increasing returns to scale when economies of scope exist.

The review article by Tovar et al. (2007) refers to three studies that explicitly address returns to scope in the port sector, namely Jara-Diaz et al. (1997; 2002; 2005). All of these studies conclude that there are economies of scope in port operations. The studies also find presence of economies of scale, but the *relative* scale advantage decrease with size.

With the exception of Tovar and Wall (2012), we have not been able to find more recent articles on estimating economies of scope for ports[11]. There has, however, been conducted several studies on economies of scope for airports; see e.g. Chow and Fung (2009).

4.1.2.2 Summarizing the literature on scale, scope, and multi—output production

Studies on economies of scale are common in port efficiency analyses. The results have been mixed, but there seem to be regular findings that technical efficiencies are increasing with the size of port operations, but that the relative scale advantages diminish with port size. However, the majority of studies have analysed single outputs, and have not addressed economies of scope. Research on economies of scope in the port sector are scarce, but a few existing studies have analysed the topic by estimating cost functions for multiple outputs, using accounting data to estimate prices for labor, capital and intermediate inputs.

An interesting aspect of the literature on economics of scope in the port sector is that it primarily represents the port technology by a cost function, as opposed to the quantity-based function representations which we described in Section 4.1.1. Hence, this literature is dependent on information about input prices. In the following, we

[10] Chambers (1988) dubs this restriction on the technology "separability in outputs".

[11] The literature review included searching Google Scholar, Science Direct, Springer Link and Taylor & Francis Online

summarize the most common definition of input prices. This description is largely based on Tovar et al. (2007).

Table 2: Output variables and input variable prices commonly used for analyzing economies of scale and scope using cost functions

	Variables (and how to calculate them)
Output variables	Tons of non-containerized general cargo Tons of containerized general cargo. Tons of liquid bulks. Tons of dry bulks.
Input variable prices	Labor price (Labor expenditure/number of employees) Capital price • The ratio between the capital cost and the active capital of the period (net fixed assets under exploitation), or: • Actual economic value of physical capital divided by the total dock length Intermediate input price: • The price of electricity as an indicator, or: • The ratio between the sum of consumption, services externally provided and other expenses, and an index of total activities represented by annual revenue

4.1.3 Multi-plant and network technologies

Section 3 described port operations in detail. The main insights brought forth by this section were:

i. ports might consist of different terminals that specialize in the handling of specific cargo types.

ii. port operations can generally be separated into different stages (e.g., the dock, the yard, and the gate) that together make up the overall cargo handling.

These characteristics suggest that it may be sensible to model port operations as if existing of multiple sub-technologies that combined make up the overall port technology.

The economics of multi-plant technologies (Sil and Buccola, 1995; Chambers, 1998) and network-technologies (Färe et al., 2000) have been thoroughly examined in production economics literature. A multi-plant technology refers to a horizontal firm structure, in which the total firm output is composed of the outputs of the firm's sub-units. For example, an electricity utility may own multiple plants that combined provide the utility's power supply. Each of the sub-units is considered having their own technology. This technology structure may be useful for ports, since they generally consist of multiple terminals (sub-units). If each sub-unit can be thought to have a separate technology (e.g., bulk and container technologies), it would be sensible to use a multi-plant-type technology to model port activities[12].

Lozano et al. (2011) apply what they dub the centralized DEA approach to examining the efficiency of Spanish ports. This model is essentially equivalent to the multi-plant technology, with the exception that Lozano et al. consider different ports belonging to the Spanish Port Agency. This is essentially a study of optimal industry structure, where two of the inputs – cranes and tugs – are assumed to be allocable among the Spanish ports in the sample[13]. Hence, the DEA model can be applied to determine the economically optimal allocation of inputs among the Spanish ports, and thereby to decide their optimal activity levels.

The network technology (Färe et al., 2000) is a generalization of the multi-plant technology that allows considering intermediate inputs and thus vertical supply structures. This approach was used by Wanke (2013) in order to separate physical infrastructure efficiency from shipment consolidation efficiency. Wanke considers the port production as a two-stage process:

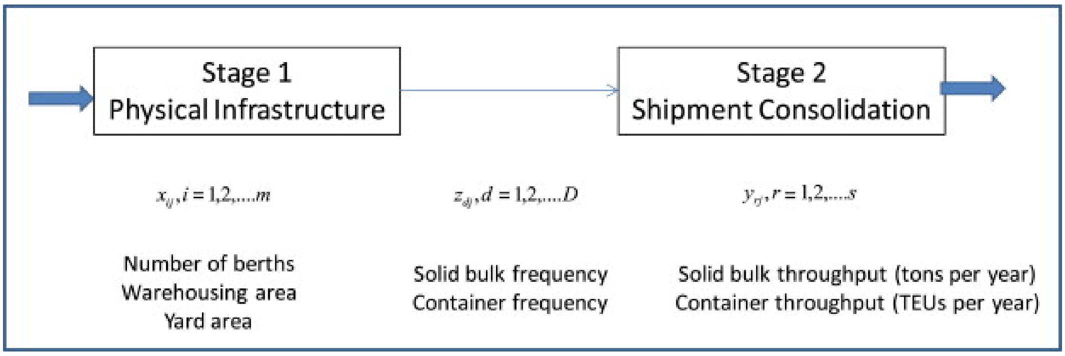

Figure 5: Port network technology. From Wanke (2013)

In the first-stage, Wanke seeks to minimize the physical infrastructure required to achieve a certain level of shipment frequency per year, while in the second stage Wanke seeks to maximize throughput for a given shipment frequency.

Bichou (2011) argues that container terminals comprise three separate sub-technologies; the dock, the yard, and the gate. Unfortunately, data limitations forces Bichou to consider a two-stage modeling of the container handling. Figure 6 illustrates Bichou's two proposed approaches to modeling container port operations. In the first scenario, the yard and the quay stages are combined into one technology, while in the second scenario the gate and the yard are combined into one technology.

12 While this is true in theory, data limitations may prevent implementing this approach (e.g. Färe et al., 2013)

13 Note also that Lozano et al. propose a rather unusual output vector, consisting of port traffic (in tons), TEUs, and the number of ship calls. Little emphasis is put on explaining the choice of inputs and outputs in the paper.

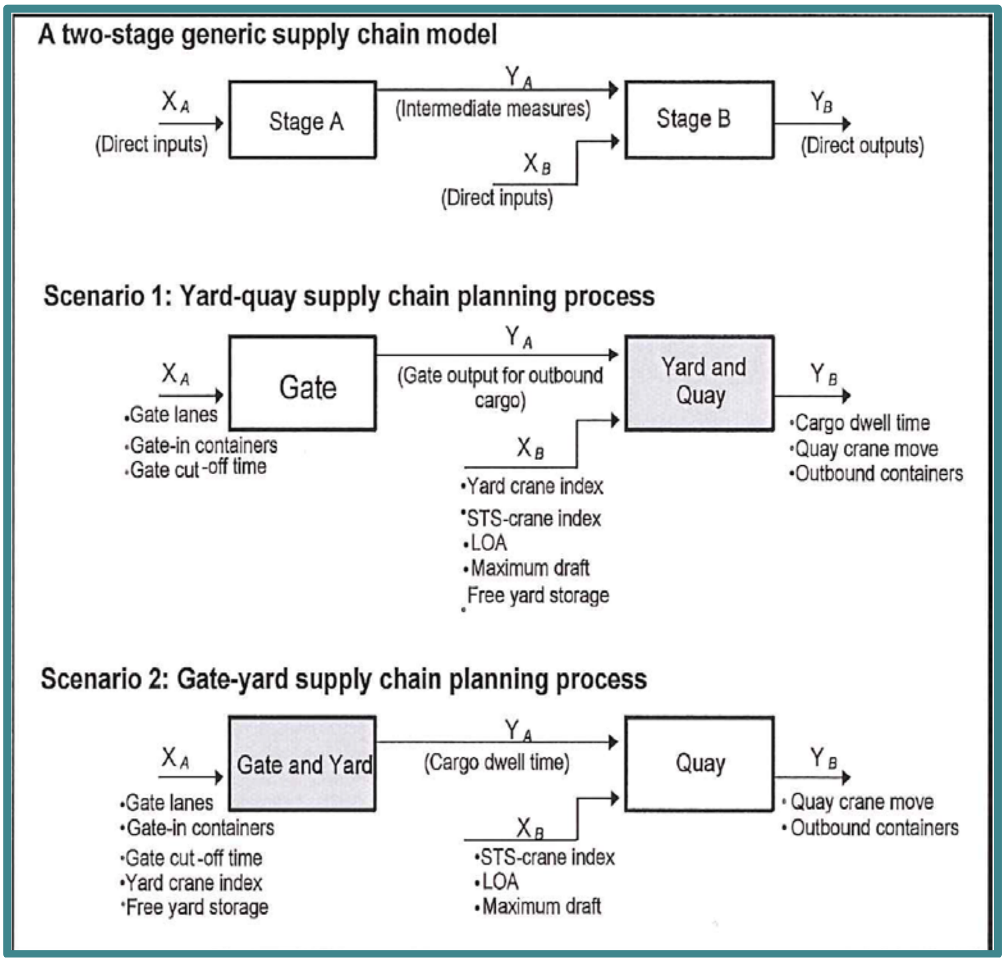

Figure 6: Two-stage technology. From Bichou (2011)

4.1.3.1 A remark on multi-plant and network technologies

A general feature of production models consisting of multiple sub-units is that they allow some inputs to be specific to the sub-technologies (non-allocable inputs) and some inputs to be allocable among the different sub-technologies (allocable inputs). This feature seems highly appropriate for ports, as we now will explain.

In Section 3, building on the work of Jara-Diaz et al. (2006), we classified inputs into common inputs, semi-common inputs, and specialized inputs. These labels referred to inputs that were common (or semi-common) to all cargo types, and to inputs that were custom-made to certain cargo types (specialized inputs).

Consider estimating cargo-specific technologies for which some inputs are cargo specific (e.g., specialized capital equipment), while some inputs are allocable to the handling of multiple cargo types (e.g., common inputs such as labor). This type of modeling is closely in line with the description of port operations in section 3. It also overcomes what we consider a potential problem with using the standard production analysis approach for modeling joint handling of multiple cargo-types (e.g., as in Jara-Diaz et al. (2006)), namely the assumption of full substitutability among all inputs in the analysis, which may consequentially result in unacceptable estimates of cargo-handling (production) possibilities and corresponding overstatement of port inefficiencies. We are unaware of research that has considered this issue, as well as our proposed modeling strategy.

The approach of fixed and allocable inputs was examined by Färe et al. (1992), who showed that the sub-unit specific input constraints could be combined into one constraint for the overall multi-plant (industry) technology for the allocable inputs. Stated differently, if there are 20 ports in the sample, then 20 input constraints can be combined into one input constraint for the overall technology. This is convenient for port modeling, because the number of potential decision-making units to be included in a port efficiency analysis is usually quite low; cf. Schøyen and Odeck (2013) who have only six Norwegian ports in their sample. This causes a "degrees of freedom" problem as the number of units is often close to the number of variables in the empirical analysis, making it difficult to distinguish efficient ports from inefficient ports. Using a multi-plant-type technology with allocable inputs may allow us to reduce the number of variables in the production model, and may act as a remedy for the degrees of freedom problem.

4.2 Port economics – with bad outputs

So far, externalities related to port operations have not been mentioned. In this section we provide a general overview of these externalities (Section 4.2.1), and present a review of the existing production analysis studies on port externalities (Section 4.2.2)

4.2.1 A general overview of port externalities

Miola et al. (2009) have conducted a comprehensive study on externalities in the maritime sector. It emphasizes externalities caused by maritime transport, specified for its different stages. Figure 7, adopted from Miola et al. (2009, p 23-24), sums up their discussion. The entire table maps out whether and how 20 maritime transport activities produce 15 types of externalities. In total, Miola et al. (2009) identify 181 relevant externality impacts caused by the 20 activities. Of these, 152 occur in ports. Some of the externalities are related to the ships, or land traffic transporting cargo to and from the port.

Miola et al. (2009) classify the externalities occurring in ports according to the recipient of the negative impacts. The five categories of recipients are air (e.g. noise and local air pollution), water (water pollution and turbidity), soil/sediment (e.g. acidification and erosion), ecosystem (e.g. biodiversity loss) and other (e.g. waste generation).

Most studies that address port externalities focus on container terminal CO_2-emissions due to the activities referred to in figure 7 as "Loading & Unloading operations on terminals" and "Bulk handling and goods movement". The studies apply energy usage factors for various port activities to calculate annual emissions. One example is Geerlings et al. (2010), who present a bottom-up methodology for analyzing CO_2-emissions from container terminals in the Netherlands.

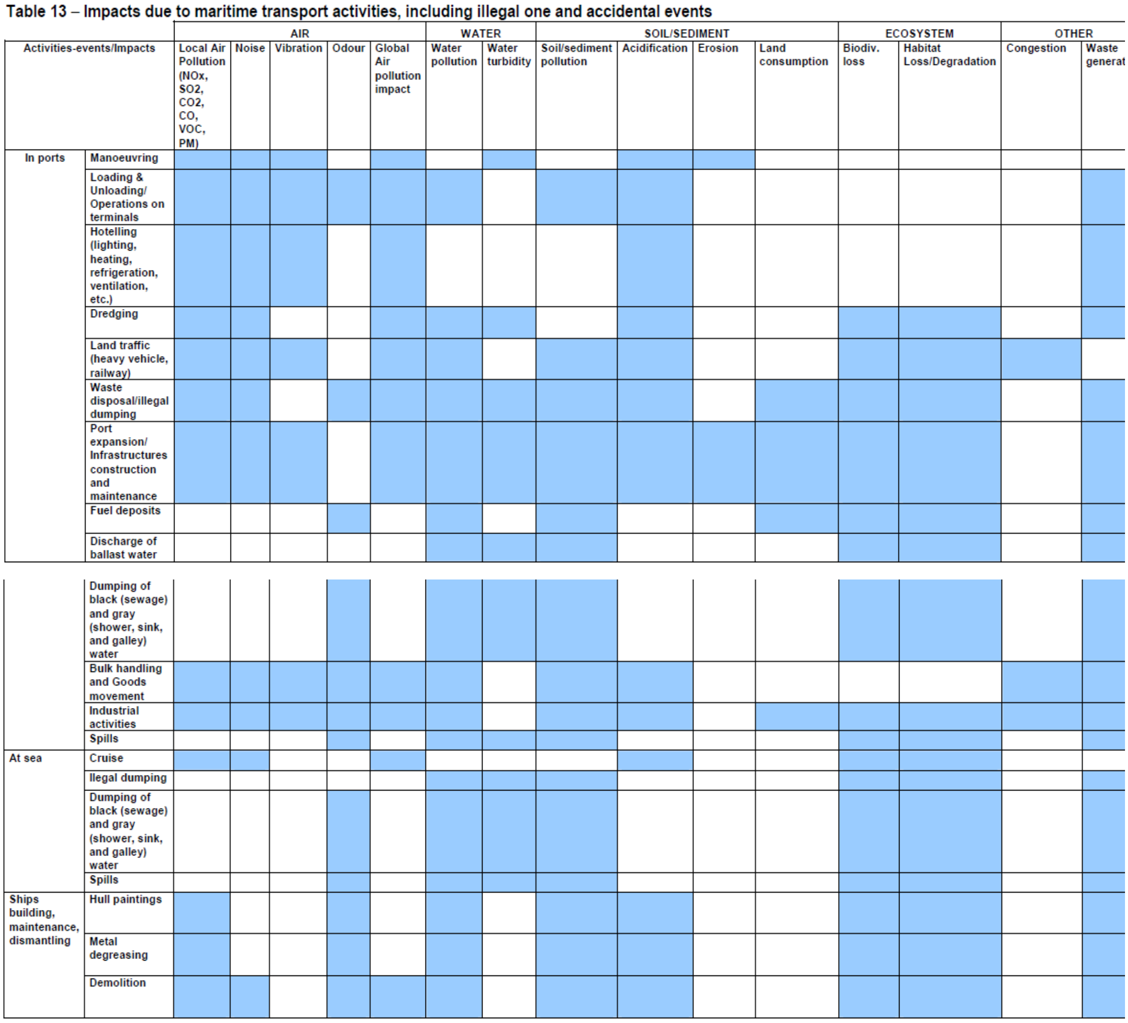

Figure 7: Overview of externalities produced from maritime activities. From Miola et al. (2009)

Even though there is some literature on the generation of externalities from port activities, there are very few assessments of their socio-economic costs. VTI (Mellin et al., 2014) have recently conducted a pilot-project on marginal cost estimation for maritime transport. This study focuses on externalities due to ship activities. In their conclusion, they state that port activities not related to ship operations should not be included in the externality assessment of maritime transport; "*Ports, like other terminals, are nodes for several modes of transports and the marginal costs of ports should not be allocated only to the maritime transports, but rather added to a transport chain*".

Del Saz-Salazar et al. (2013) provide a methodological approach for economic appraisal of port externalities, and conducts a valuation exercise for the port of Valencia. They use the contingent valuation method (CVM) to assess how much the affected population would need in compensation to be willing to accept (WTA) an expansion of the Port of Valencia with the entailed negative externalities. Their results indicated that the Valencians would be willing to accept a compensation of approximately 40 million EUR. The authors also estimated that the affected population would be willing to pay (WTP) approximately 70 million EUR for redeveloping Castellón harbour to recreational areas. The latter result illustrates the opportunity cost of land-use for port-purposes.

4.2.2 Bad outputs in port efficiency analyses

A few recent port efficiency analyses have included externalities or undesirable outputs. This follows a general trend in the productivity and efficiency analysis literature, in which the treatment of undesirable outputs currently receives much attention.

Chang (2013) evaluates the environmental efficiency of 23 Korean ports. His analysis builds on the slack-based efficiency measure, and assumes that undesirable outputs are appropriately modelled as freely disposable inputs[14]. The number of workers, the length of the quay and the terminal area, and the energy consumed are thought to be the relevant inputs, while the outputs are vessel tons, cargo tons, and carbon dioxide emissions. The latter variable is collected from a report by a Korean ministry (KMI).

Chin and Low (2010) do also use a slack-based efficiency measure, also assuming that undesirable outputs are equivalent to freely disposable inputs. This study emphasizes CO_2, NO_X, SO_2, and particulate emissions from ships rather than from port operations, and analyzes the technical and environmental efficiencies of 156 O-D pairs between 13 ports. This study utilizes data on ship activity to calculate energy use and emissions.

Haralambides and Gujar (2012) propose an eco-DEA model, which is applied for evaluating the efficiencies of Indian dry ports (inland cargo-consolidation and distribution centres). In this paper, the undesirable output, carbon dioxide emissions, is modelled as a freely disposable output[15]. CO_2 emissions are calculated based on estimates of the actual amount of cargo transported and the energy consumed per unit of output

Yang (2012) focuses on the water quality of Taiwanese ports, using data from the Taiwanese Environmental Protection Agency. He defines water quality indicators that are increasing as the water quality improves, and can therefore be treated as freely disposable outputs in the efficiency analysis. Despite the many possible indicators for water quality that exists (e.g., PH value, dissolved oxygen (DO), biochemical oxygen demand (BOD), cyanides and oil), Yang could only obtain data for DO. The author stresses the importance of including water quality into efficiency analysis, especially when comparing ports across countries. Regulations and compliance vary across countries, meaning that countries that apply much effort to improve the water quality are not rewarded for their efforts and are likely to turn up as inefficient if the efficiency analysis ignores water quality.

Lee et al (2014) use a slacks-based DEA approach to analyse the environmental efficiencies of 11 port cities. Their results suggest that increased efficiency can increase container throughput and regional GDP and at the same time reduce the use of labor and the extent of pollution (CO_2, NO_X and SO_2). We consider this paper to have several shortcomings.

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[14] Let x denote the input vector and T denote a set-theoretical representation of the port technology. Free disposability of inputs is then defined by the mathematical statement " if $x \in T$ and $x' \geq x$, then $x' \in T$ "

[15] Let y denote the output vector and T denote a set-theoretical representation of the port technology. Free disposability of outputs is defined by the mathematical statement " if $y \in T$ and $y' \leq y$, then $y' \in T$ "

4.2.2.1 Summarizing the literature on Port economics—with bad outputs

Our literature review shows that there are only a few port efficiency analyses that include externalities. The primary concern of these papers has been on air pollution (mainly CO_2 emissions), but one paper considers water quality. Both types of externalities can be important for the evaluation of socio-economic efficiency of ports. However, measuring water quality can be complicated, since there may be multiple sources of poor water pollution other than the port. Examples include runoffs from the agricultural and industrial sectors.

We are – with the exception of Yang (2012) – questioning the appropriateness of the proposed modeling approaches chosen by the efficiency analyses. Two studies, Chang (2013) and Chin and Low (2010), model air pollutants as freely disposable inputs. This is a questionable assumption since the studies thereby assume full freedom of substitutability among air pollutant and other inputs. Of particular concern is that the studies include energy inputs, and therefore assume that energy can be traded for air pollution emissions. This is not consistent with the laws of physics (the first law of thermodynamics), which imply that energy and air pollutants are complements.

Haralambides and Gujar (2012) assume that pollutants can be modelled as freely disposable outputs. This essentially means that pollutants can be reduced (and even omitted) at no costs, which seems highly unrealistic. See Førsund (2009) for a critical discussion.

Finally, we note that the concepts of economies of scale and scope have traditionally been examined by the use of economic models that do not include unwanted byproducts (pollutants). Thus, potential environmental-economic trade-offs are generally overlooked. The concept of damages to scale (Sueyoshi and Goto, 2010) has recently been introduced to address this issue. Sueyoshi and Goto have, however, not focused their studies on ports, but on electric power generation.

5 Other issues on modeling port operations

This section takes up other points for discussion, some of which we feel have not been properly addressed by the existing literature on port economics

5.1 Separability and nonjointness

Section 3 reviewed port operations, and portrayed them as "a large number of smaller operations, most of which form a successive links of chain" (Jara-Diaz et al., 2006 p. 67), in which several common or specialized inputs are employed. Bichou (2011) and Carlo et al. (2014) argued that container terminal production can be viewed as consisting of three stages; the quay, the yard, and the gate.

We explain the concept of a *separable* technology with the following: An overall production process can be broken into stages. At each stage, some inputs are used to make an intermediate input, that is used together with other intermediate inputs to make the final product. Formally, this means that the marginal rate of technical substitution between two inputs are independent of the use of other inputs that are not relevant to the sub-production in question. Further, if ports can be viewed as consisting of separate technologies for each cargo-type, we say that the technology is *nonjoint in inputs*.

Separability and nonjointness are well-known structural characteristics of the technology; see Chambers (1988) for details. Thus, it is possible to develop empirical tests that can verify whether the port production indeed satisfies any of these characteristics. Such tests can be helpful in finding an appropriate specification of port technologies. We are unaware of any studies that actually undertake such tests. Some studies, e.g., Bichou (2011), make a priori assumptions about the correct specification of port technologies, but do not consider empirical testing for aiding the appropriate port modelling.

5.2 Selection of input and output variables

Cullinane and Wang (2006) provide guidelines for the selection of variables for efficiency assessments of container ports. They emphasize that understanding a port's objective is important for identifying which variables that are relevant to consider. "*For instance, a port is more likely to utilize state-of-the-art, expensive equipment to improve its productivity if its objective is to maximize cargo throughput. On the other hand, a port may be more willing to use cheaper equipment if its objective is simply to maximize profits*" (Cullinane and Wang, 2006 p. 538). This point is also of importance with respect to the choice of functional form used for the efficiency assessments (e.g., distance functions, cost functions, or profit functions), because they each impose different assumptions about the economic behavior of ports.

5.3 Contextual variables

Section 4 emphasized the most common choices of input and output variables in port economics. The variables described are generally factors which are under the control of ports. However, the productivity and efficiency of ports may also be affected by other factors that are not under the control of the port mangers. A typical example is public regulations that influence port activities. We dub such factors contextual variables.

We are only aware of a few studies on port economics that actually consider contextual variables. Wanke (2013) use DEA and second-stage regression to examine the influence of contextual factors on port performances. The contextual variables he considers are:
- Private administration (dummy)
- Hinterland (Sq. Km)
- Number of highway accesses
- Riverine access (dummy)
- Railroad access (dummy)
- Number of accessing channels

Yuen et al. (2013) undertook a second-stage regression analysis to account for:
- Ownership (Chinese and non-Chinese)
- Hinterland population
- Hinterland GDP
- The degree of inter-port competition (the log distance of the seaport where a particular container terminal located from the nearest other seaport)
- The degree of intra-port competition (number of the container port terminal operators at the port city)
- The average wage

Johanna Ludvigsen held a presentation on contextual variables for ports at EXPORT's kick-off meeting. She pointed to that ports interact with their hinterland. One example is that the hinterland industry structure largely determines which cargo types are handled by the ports. Thus, changes in the hinterland structure will largely influence port activities. Such changes will for example influence what types of ships that arrives, and in turn which requirements there are for cargo handling and security. Further, the ports' locations, e.g. in the proximity of a large population, will also play an important role for degree of regulation of port activities; cf. noise regulations.

Kenneth Løvold Rødseth commented on the modelling of contextual factors in production analysis in one of his presentations at EXPORT's kick-off meeting. He first reviewed the pros and cons of DEA and SFA, namely that DEA is a non-parametric but deterministic technique while SFA is a stochastic but parametric technique. Thereafter, he reviewed the most common approaches to treating contextual variables using DEA and SFA[16]. He concluded that all of these approaches have shortcomings, and he suggested that the new StoNED model (see

[16] We will not cover this point in detail since the slides from the kick-off meeting, containing the appropriate references and discussion, are available on EXPORT's web page.

e.g. Kuosmanen (2012)) could be a valid alternative to the DEA or SFA model. This model is non-parametric and stochastic, and is also highly appropriate for modelling contextual variables.

5.4 Integer variables

Section 4 reviewed the most common input and output variables in port economics. Several of these variables, such as the number of cranes and tugs, are integer variables (Lazano et al., 2011). This causes problems, because traditional production analysis approaches such as DEA or SFA assume real-valued inputs and outputs. While rounding off performance targets to the nearest whole number is unproblematic for integer variables that take very high values, it can make a large difference for variables that take a small number (Kuosmanen and Matin, 2009). The number of e.g. cranes in a port are usually very low, and modification of the standard methods (e.g., by using the integer DEA approach of Kuosmanen and Matin (2009)) should be considered.

5.5 The operating configurations of container ports

Bichou (2011) argues that there are three major shortcomings of the contemporary production analysis literature on port economics (which was reviewed in Section 4), which relates to what he perceives to be the literature's inability to incorporate the actual operating configurations of container ports and terminals.

- Variations in port operating configurations and technologies are hardly captured by the existing literature: Most authors consider the number of quay and yard cranes as inputs to port operations, but fail to incorporate variations in the performances of different crane types
- Container yard configurations come with a variety of cargo handling and stacking typologies, including the tractor chassis system and the straddle carrier direct system, each with different performances and technological characteristics
- Port operators may design and implement different operating procedures, e.g., opening and service hours, gate-in gate-out arrangements, and cut-off times for loading.

Bichou proposes to deal with the variations in operation configurations using indices that account for the technical variations of different equipment. One example is Bichou's (2011, p. 16) yard crane index:

$$\text{Yard crane index} = \text{Yard staking crane (number)} \times \text{Ground storage capacity} \times \text{Stacking height}$$

We note that another solution to this problem would be to recognize that cranes are heterogeneous, and thus to treat different cranes types as separate inputs rather than merging the number of cranes into one input.

5.6 Economies of scale vs. Economies of density

Our review of the literature on production analysis of ports has shown that a majority of studies consider stock variables rather than flow variables as the main input to port operations. Examples include the number of cranes, the size of the port's land area, and the length of the quay.

Several terminal studies set out to consider returns of scale or scale efficiency. By returns to scale, we here mean the maximal proportional increase in (desirable) outputs facilitated by a proportional increase in inputs. Taking into account the input variables commonly used in container terminal studies (i.e., the stock variables), it follows readily that the definition of returns to scale in the port economics literature generally refers to a physical expansion of the port area and the port's equipment stock.

Caves et al. (1984) coined the term economies of density, which unlike economies of scale refers to the variation in unit costs caused by increasing transport services within a network of given size. A parallel definition would in our setting be to examine the variation in unit costs caused by increasing cargo handling for a given port area and capital equipment. This measure of economies of density is thus a measure of the *capacity utilization* of the existing port infrastructure rather than a measure of the economies of *port expansions*.

Previous studies have suggested that there are sufficient capacity, if not overcapacity, in the Norwegian port sector; see Rødseth and Killi (2014). Thus, the measure of economies of density is likely to be more relevant for modelling present days' port operations in Norway than the measure of economies of scale (port expansions).

5.7 Good modelling of bad outputs from port operations – an emphasis on stochastic load

Recently, there has been an increasing interest in modelling the joint production of good and bad outputs in the production economics literature. This has led to the introduction of a handful approaches to modelling bad outputs. We can broadly classify them into two categories, the economic approaches and the physical approaches. The best-known economic approaches are:

- Modelling pollutants as freely disposable inputs; e.g., Pittman (1981)
- Modelling pollutants as weakly disposable outputs; Färe et al., (1989)
- Modelling pollutants as costly disposable outputs; Murty et al., (2012)

In Section 4.2.2, we found that most production analyses of ports containing bad outputs model pollutants as freely disposable inputs. This is not in line with recent developments in the productivity and efficiency analysis literature, where the approach of Färe et al. (1989) has become the most popular tool for empirical environmental efficiency analysis. However, several recent papers criticize Färe et al.'s weak disposability approach for not complying with certain physical laws that are relevant for explaining and modelling pollution generation. This literature has in particular emphasized the inconsistency of the weak disposability assumption and the materials balance condition; see e.g., Coelli et al. (2007). The materials balance condition is particularly important for modelling air pollution emission stemming from the use of fossil fuels, and thus relevant for a wide range of energy-using port activities.

Several physical approaches that secure the consistency of the production model and the materials balance conditions have been proposed:

- Multi-ware production (Førsund, 2009)
- The "cost-function" approach (Coelli et al., 2007)
- Weak G-disposability (Hampf and Rødseth, 2014)

While the materials balance condition has received much attention in the literature, the modelling of other types of pollution such as noise and vibrations is yet to be formally treated and discussed. Noise, which is a likely to be an important externality related to port operations, is measured on a logarithmic scale (Decibels). Treatment of noise in production analysis may therefore require modification of the standard tools, since production models traditionally handle real-valued inputs and outputs. We consider this issue parallel to the integer number problem described in section 5.3. Noise emissions and their damages are also largely dependent on a series of factors usually not considered in production analysis, such as vehicle speed, the time and location where the emissions take place and so forth. See e.g. Andersson and Ögren (2013) for an approach to calculating marginal external noise costs using engineering methods to calculate noise emissions.

Our literature review on externalities in Section 4.2.1. show a large number of externality creating activities in ports and many different types of externalities affecting air, water, soil, ecosystems and other. In Section 4.2.2, we see that CO_2-emissions, local air pollution and water pollution are the externalities that so far have been included in port efficiency analyses. This implies that there are still many types of externalities yet to be included in port efficiency analyses. However, it is not only a question of including different types of externalities, but also addressing the different nature of the different externalities. For instance, emissions to air or noise are closely related to the activity level, while emissions to sea and land are stochastic events, often related to human error or equipment malfunction.

Production risk has received much attention in the literature on agricultural economics. Reviewing this abundant literature is a demanding task, and we will therefore refrain from pursuing this trail further at this point. However, we would like to mention the seminal risk-assessment model by Just and Pope (1978), which has been heavily exploited for assessing production risk in the Norwegian salmon industry. This model assumes a stochastic representation of the production technology (i.e., the production model includes an error term – which is the case both for the SFA and StoNED), where error term variations are perceived to be manifestations of production risk. Thus, second stage regressions, explaining the error term variations, are used to identify factors that are risk-increasing and risk-reducing.

5.8 A follow-up comment on the use of stock and flow data

So far, we have considered the literature on port economics and reviewed the most common data used by these studies. We have found that terminal studies generally use stock data (e.g., the number of cranes) or accounting data (e.g., expenditures) for inputs, while the literature on economies of scale and scope uses input prices (e.g., wages).

One of EXPORT's main objectives is to estimate external costs due to port operations. This means that using stock data on equipment etc. is likely to be of less relevance to the project. Using stock data for inputs along with (activity-dependent) pollutants to estimate the port technology may in fact lead to biased estimates of environmental efficiency, a point which we now will explain.

Assume for example that we are interested in comparing two ports' CO_2 emissions, and that both ports own the same number of equipment. Notice also that CO_2 emissions are directly related to the consumption of fossil fuels by the materials balance condition. Hence, they are related to the ports *use* of their equipment.

Assume that one port handles more goods than the other port, which, ceteris paribus, will imply that the high-activity port exhibits higher CO_2 emissions than the low-activity port. Consider now estimating a "production function" which explains CO_2 emissions by the amount of equipment. Since we here consider the amount of equipment, not the use of the equipment, our results will indicate that the low-activity port is more environmental efficient than the other port, because it produces lower CO_2 emissions for the same amount of inputs (equipment). This, however, is only a result of the input choice, and does not reflect the actual differences in environmental performances. If the use of the equipment rather than the stock of equipment were reflected by the input data, this problem would readily be resolved. Thus, we keep this point in mind when we now present an overview of potential data-sources for the EXPORT project.

6 A mapping of available data

We classify the available data into three categories:
i) Activity data
ii) Environmental data
iii) Other data

6.1 Activity data

There exists a wide range of data sources that can help describe activities in Norwegian ports. The various sources will together generate a comprehensive picture of the status and developments in port activities, although gaps in the overall data material and overlaps among different data sources are expected. Different data sources may involve different level of aggregation (e.g., for the port or the terminal), and relevant variables may only be available for one or few years (e.g., noise emissions), thus making it challenging to compile data on all relevant variables for a given year (i.e., a cross-section dataset) or a given time period (i.e., compiling a panel dataset). In short, we expect working with the various data sources to have elements of a "puzzle work". Personal contact with various port authorities, and perhaps even surveys, might be necessary to verify the quality of the data and/or filling the gaps in the available data.

EXPORT-partner Halvor Schøyen has collected a panel dataset for the period 2003-2008 for 24 Norwegian and foreign container ports that may be used as the basis for the project dataset. Schøyen's dataset is based on the Containerization International Yearbook (CIY), and provides information about input variables such as berth length, quay and yard gantry cranes, terminal areas, straddle carriers, and trucks. Schøyen made personal contact with the ports to get additional information/verification of the data.

TØI has access to the raw-data underlying Statistics Norway's "port statistics" (SSBs Havnestatistikk). It provides detailed activity data for Norwegian ports, e.g., information on ship types, ship sizes, cargo types, cargo volumes and on the amount of time that ships spend in port. For time spent in ports we will most likely only be able to obtain data for 2011 and 2012, but for other relevant variables we can obtain data for a longer time span. Publically available statistics on the port level are available for years between 2003 and 2014. With the exception of (most) of the mentioned time-use-registrations that are reported on the quay-level (and thus are reported on a more disaggregated level than the terminal level), the port statistics is generally only available on the port level. In order to do analysis on terminal level, assumptions based on cargo types and ship size thus need to be made. TØI has conducted several analyses of the raw data underlying the port statistics (see e.g., Wangsness and Hovi, 2014), and is familiar with the strengths and weaknesses of this data source.

We will be able to obtain financial data from various sources. Some ports publish detailed annual reports with key financial variables. However, not all ports provide sufficiently detailed accounting data, and some of them do not even publish annual reports (e.g., due to how they are organized under the municipality) [17].

Financial data for publicly owned ports may also be available from Statistic Norway's KOSTRA database (Municipality-State-Reporting). We have been in touch with Statistics Norway, who have filed an application to the Ministry of Local Government and Modernization (the owner of the data). We are expecting an answer from the Ministry within a short period.

Key financial variables (e.g., running expenses, investments, and gross operating profits) for several agents involved in port activities may also be obtained from Statistics Norway's structural business statistics. We have been in contact with Statistics Norway to obtain the raw data (or at least disaggregated data) underlying the structural business statistics for terminal and quay operators and cargo handlers.

It may also be possible to obtain other key financial variables from the BOF-register (Bedrifts og foretaksregisteret). The Institute of Transport Economics has acquired access to some of the material in this database, and is now considering acquiring more data[18]. Some of the ports' key financial data (the ports that are registered as corporations, though often owned by one or several municipalities), can be obtained for a longer time series at Proff®Forvalt (forvalt.no). This data is publically available. As mentioned earlier in this section, it is possible to obtain data from many different sources, but combining them to obtain an appropriate dataset for EXPORT will require some puzzle work.

The financial data will allow for several analyses on efficiency aspects, but they can also help obtaining variables necessary for production analysis. In particular running expenses can be useful for EXPORT, because it will allow deriving input quantities if prices are known. In particular, the energy use is highly relevant for calculating emissions to air. If energy prices are known, the total energy use (and thus air pollution emissions) can be determined on the basis of the reported energy expenses. Wages and other input prices can also be determined based on the accounting data.

Regarding physical inputs, the ports' annual reports can also be a source of data on employment, equipment, operating costs, operating revenues, investments, cargo throughput, and some environmental data intended for Health, Environment and Safety (EHS) purposes.

In Section 6.2, we emphasize environmental data for ports. There we discuss more about the Norwegian ports' liability to report their noise emissions every 5 years. Because of this requirement, noise-mapping reports that contain detailed activity data are available. The activity data from the noise reports are clearly highly relevant for the EXPORT project, as the following example from the port of Borg suggests:

[17] By undertaking a quick search online, we were able to locate the annual reports for 2013 for 10 of the largest ports in Norway, containing detailed accounting data. We believe that a more extensive and detailed search will allow us to locate this information for a substantial amount of Norwegian ports, and we therefore consider the annual reports to be a viable source of accounting data.

[18] The variables which are likely to be acquired are sales (revenues), labor, general intermediates (combined expenses), and the total value of capital assets.

Table 3: Activity data from noise reports. From Fredrikstad kommune (2012)

Tabell - Støykilder med driftstimer pr. år i 2011, lydeffekt pr. maskin ved full drift og omregningstall (dB) til drift i et årsmidlet døgn og en normal natt. Lydeffektene inkluderer både maskin- og prosesstøy. Evt. skjerming rundt støykildene er ikke inkludert i verdiene.

Type støykilde	Driftstimer pr. år 2011	Lydeffekt pr. maskin ved full drift	Omregningstall (dB) til døgn år 2011	Omregningstall (dB) til natt år 2011
Containerhavn				
Truck	5200	109	2,2	-4,9
Kran	1800	108	-0,8	-8
Terminaltraktor	250	111	-1,4	-8,6
Båt	2200	100	0,2	-7
Bulk- og stykkgods				
Kran	900	108	-9,5	Ikke nattedrift
Båt	1800	100	-6,8	Ikke nattedrift
Annet utstyr (hjullaster, etc.)	Inngår i andre kilder			

6.2 Environmental data

Environmental data related to port activities are essential to our project. The existing literature on external costs of maritime transport has mainly emphasized pollutants from ships, while the current project focuses specifically on external costs due to port operations. The following discussion on data will therefore emphasize environmental problems due to port activities.

The magnitudes of air pollution are usually estimated by combining activity data with emission factors. There are several publicly available sources of emission factors for air pollutants, but we consider LIPASTO (http://lipasto.vtt.fi/indexe.htm) to be one of the best for maritime transport, including cargo handling in ports. LIPASTO provides emission factors for a wide range of working machines used in ports.

Norwegian ports comply with the public act concerning protection against pollution and concerning waste (hereafter, the pollution act), that includes EU-standards on noise emissions. As a result, they are obliged to provide detailed mappings of noise due to their activities every five years. The results from these surveys are publicly available for the largest ports in Norway.[19]

We will consider several data sources for information on water and soil pollution:

First, the Norwegian Coastal Administration presents weekly detailed reports on the locations and magnitudes of reported oil spills in Norway. By examining these reports, we will be able to gather data on oil spills related to port activities.

Second, 28 ports have been asked by the Norwegian Environment Agency to provide mappings of contamination of their surrounding seabeds. The project leader (TØI) has been in touch with Senior Engineer Kristine Mordal Hessen of the Norwegian Environment Agency, who confirmed that the 28 reports could be made

[19] See http://www.oslohavn.no/filestore/PDF/2014/2014rsrapportSWECOfor2013OsloHavn-StymlerOrmsundogSjuraya.pdf for an example from the port of Oslo.

available to the project team. Erik Høygaard of the Norwegian Environment Agency participated in EXPORT's kick-off meeting to provide further details on these reports. He explained that one of the main environmental concerns about port activities are dispersion of pollution stored at the seabed, induced by ships arriving and leaving the ports. Turbidity is a useful measure for this type of pollution dispersion. Data on turbidity is available from the Norwegian Environment Agency's reports.

Third, we will consider the possibility to include water or soil quality indices to approximate accidental spillages; cf. Yang (2012). In Norway, the Environment Agency provides a database on available reports about the water quality in Norway. This data is available at http://vannmiljo.miljodirektoratet.no/. The project leader has been in touch with Senior Researcher Are Pedersen at NIVA, who recommended vannportalen for data collection. Erik Høygaard proposed grunnforurensingsdatabasen (http://grunn.klif.no/) as a possible source of data for soil emissions. This database contains information on more than 3000 properties in Norway, on which soil contamination has been identified. The water and soil contamination databases provide soil and water quality reports for specific geographical areas, laid out on a map of Norway.

The pollution act requires all Norwegian ports to collect waste from ships and further to develop strategic plans for waste collection. Because of the act, Norwegian ports are obliged to report the amount of waste collected from ships to the Norwegian Maritime Authority. The Norwegian Environment Agency has also recently inspected the waste management of Norwegian ports. EXPORT's project leader has been in touch with the agency to get more information about the outcomes of their surveys. A conversation with senior Engineer Håkon Oen of the Norwegian Environment Agency on October 4th, 2014, revealed that there are negligible external costs related to waste management, and that there are no appropriate data collected to report such costs. However, we note that the purpose of enforcing waste management in ports is to prevent external costs, namely emissions to sea due to dumping of garbage at sea.

Data on personal injuries related to port activities are available from two sources. Data on ship crewmembers' injuries in ports can be collected from the Norwegian Maritime Authority's accident database (which the Institute of Transport Economics already has access to). Second, all ports are obliged to report work injuries to the Norwegian Labor Inspection authority.

Possible environmental data could also be related to complaints to ports, i.e. complaints could possibly be used as proxy variables. Information about complaints could be obtained from the ports (e.g., The Port of Oslo has a digital complaint process for noise on their web site), or from the relevant municipalities.

6.3 Other data

We will also compile information on relevant contextual variables (variables that are not under the control of port managers). These variables may include geographical information, information about the hinterland, on legislations, etc.

Unit prices (monetized damage) are required to calculate external costs of port operations. Unit prices for the Norwegian transport sector have recently been revised by TØI (Samstad et al., 2010). International studies (e.g. the EC-funded HEATCO project) will also be considered. It is outside of the scope of the EXPORT project to undertake own assessments of damage costs.

All public ports in Norway report their default prices and fees, e.g., fee per port call, fee per container, fee per lift by crane and so on. It should be noted that many of these prices and fees are, according to the port's fee documents, open for negotiation.

Statistics Norway's road freight transport survey (lastebilundersøkelsen) can be useful for examining hinterland freight transport, by providing information on road freight transport at the municipality level.

7 Discussion

The previous sections of this report have identified best practices for production modeling of port operations, and have described a wide range of available data. In this section, we provide some further discussions on appropriate modeling and data collection strategies.

7.1 Where are the boundaries of port operations?

In Section 4.2, we provided an overview of external costs due to port activities. It showed that port externalities are both related to activities inside the port areas, but also to ships and to road- and rail transport. We noted that external costs due to ship activities and rail- and road transport are far better understood than external costs due to activities taking place inside the port area (e.g., related to transfer vehicles and cranes).

Section 4's review of the port economics literature suggests that good data on activities taking place in ports is scarce. The majority of studies assume that stock variables like the number of cranes and tugs are good proxies for inputs used for cargo handling, and there are only a few studies that attempt to explicitly model different stages or areas of port activities; e.g., Bichou (2011).

Based on these findings, we conclude there is little available knowledge about land-based port operations and their externality generation, while connecting transport by ship, truck, or rail is better understood. Thus, it seems reasonable for the EXPORT project to focus its attention to land-based port activities, and possibly, to exclude externalities from ships and the connecting land transport. There is also a question of double counting the external costs if pollutants connected to ships and the modes of land transport are both included in the ports' pollution accounting and in the mode-specific pollution accounting.

On the other hand, good data on port activities may be hard to come by. This is also reflected by our data mapping, where some of the best available data (e.g., the port statistics) primarily covers the cargo throughput, but not variables related to e.g. the use of cargo handling equipment. However, in Section 6.1, we argued that the available annual reports, financial and employment data from Statistics Norway's KOSTRA statistics and structural business statistics, the BOF-register and Proff-forvalt, along with ports' noise mapping reports, together will provide detailed data on port activities. By combining these viable sources, filling gaps and handling overlapping data, we may be far better equipped to model port operations compared to the previous studies using production analysis to ports

In addition, other activities should perhaps also be considered when deciding the boundary of port operations. This could be activities such as icebreaking, pilotage and various passenger services.

7.2 Which externalities should we consider?

Miola et al.'s (2009) overview of externalities due to maritime transport, which was reproduced in Section 4.2., shows that loading and unloading operations on terminals produce a wide range of externalities. The most important are:

- Local air pollution
- Global air pollution
- Noise and vibration
- Odor
- Water pollution (due to accidental leakage)
- Soil and sediment pollution (due to accidental leakage)

If port expansions are considered, then impacts on the eco-system can also be expected. In Section 5, we explained that port expansions may not be relevant for Norway, and we therefore consider these implications to be of less relevance to the EXPORT project at this point.

Since the list of potential pollutants is long, but the sample sizes for port efficiency analysis usually are quite small, it may be necessary to prioritize which external impacts we should consider. The European Sea Port's "ESPO Green Guide" (2013), which lists the environmental priorities of port managers in the European member states, is a possible guide for such priorities. 122 ports from 20 European Maritime States participated in this survey. Figure 8 presents the top 10 environmental priorities for 1996, 2004, and 2009. Environmental issues that consistently appear over time are mapped with the same colour. The EcoPorts network (where the ports of Oslo and Kristiansand are members, www.ecoports.com) is integrated in ESPO, where ESPO offers the opportunity to its member ports to use the well-established tools, such as the Self Diagnosis Method (SDM) and Port Environmental Review System (PERS). ESPO monitors members' performance through analysis of results from the SDM. Darbra et al. (2004) and EcoPorts (2011) explain the SDM in more detail.

Table 1: Top 10 environmental priorities of the European port sector over time

	1996	2004	2009
1	Port development (water)	Garbage / Port waste	Noise
2	Water quality	Dredging: operations	Air quality
3	Dredging disposal	Dredging disposal	Garbage / Port waste
4	Dredging: operations	Dust	Dredging: operations
5	Dust	Noise	Dredging: disposal
6	Port development (land)	Air quality	Relationship with local community
7	Contaminated land	Hazardous cargo	Energy consumption
8	Habitat loss/degradation	Bunkering	Dust
9	Traffic volume	Port development (land)	Port development (water)
10	Industrial effluent	Ship discharge (bilge)	Port development (land)

Figure 8: Sea Port managers' top 10 environmental priorities

One of the main environmental concerns about port activities are dispersion of pollution stored at the seabed, induced by ships arriving and leaving the ports. Turbidity is a useful measure for this type of pollution dispersion. Data on turbidity, the cloudiness or haziness of a fluid caused by individual particles, is available from the Norwegian Environment Agency's reports from 28 Norwegian ports, as mentioned in Section 6.2.

Air pollution emissions from ships have received much attention in the international literature; see Miola et al. (2009) for an overview. As far as we understand, the majority of ship emissions studies rely on AIS-data (ship-movements data) to calculate emissions and external costs. However, activity-based modeling of fuel consumption and emissions does to our understanding not factor in the time which ships spend in ports, and thus overlook the corresponding in-port air pollution emissions[20]. Air pollution emissions taking place in ports have a much greater damage potential than air pollution emissions taking place at sea, because of the proximity to greater populations. The EXPORT project has access to Statistics Norway's port statistics, which readily allows us to calculate the amount of time that ships spend in ports.

In addition to the already mentioned external costs, we may also consider other costs that to varying degrees are associated with port activities. First, personal injuries are a common external cost in the literature on transport externalities, but which we suspect is internal to the port sector by insurance. However, there could be non-internalized accident-related costs for other parties working in the port areas (e.g., Customs) or other parties being in the port area for non-work reasons (e.g. alcohol)[21]. Second, congestion and waiting time in ports are likely to depend on the ports' efficiencies in loading and unloading cargo. However, previous studies have concluded that Norwegian ports have sufficient capacities to ensure that congestion costs for ships are negligible (Rødseth and Killi, 2014). Congestion costs are also considered a negligible part of the external costs in the maritime sector by Miola et al. (2009). Third, alternative use of areas occupied by ports may provide higher rents (see e.g., Del Saz-Salazar et al. (2013)).

The list of potential externalities is long, and we believe that the need for prioritization is in place. Based on the previous discussion, we propose at this point to emphasize the following externalities:

- Turbidity (pollution dispersion) due to ships entering and exiting the port
- Noise and air pollution emissions due to cargo handling in ports
- Air pollution (local and global) from ships at berth and cargo handling in ports. We will return to this point in Section 8.
- Soil and sediment (and water) pollution due to accidental spills. As mentioned in Section 5.7., the handling of these externalities would require models that deal with production risk.

[20] Recall that while fuel consumption and emissions at sea of course is related to the main engine(s), it is related to generators when the ships are in port.

[21] Note that ISPS regulations should keep unauthorized personnel out of the port terminals, thus counteracting this issue.

7.3 How should we model port operations?

In section 3, we reviewed port operations, and showed that they are both comprised of a series of different operating stages and of common and specialized inputs. We pointed out the possible existence of economies of scope in handling multiple cargoes.

In Section 4.1.3.1, we proposed a new production modelling approach for ports in which ports are assumed comprised of cargo-specific technologies, where some inputs are cargo-specific while other inputs are allocable among the different cargo types (or technologies). We believe that our approach allows dealing with economies of scope due to common inputs, but at the same time to avoid unrealistic efficiency estimates related to inappropriate treatment on substitution possibilities for cargo-specific inputs. The con of this approach is, however, the accessibility to appropriate data.

We have showed that a majority of existing papers on production modelling utilize stock inputs, such as the number of cranes and tugs. This is problematic if the ports' utilization of their equipment is poorly correlated with their capital stock. Second, the existing efficiency analyses of ports do generally not take the time of loading and unloading cargo into account. This aspect can be important, because the time-use can have an impact on:

- The time which ships spend at the quay, and thus for the ships' in-port air pollution emissions[22]
- Congestion costs; if the port's capacity is fully utilized, arriving ships will have to wait until one or more ships leave the port. The waiting time is negatively correlated with the time it takes the ports to load and unload cargo.

We note that reducing the loading/unloading time may be resource demanding[23] (e.g., by demanding more labor), and is therefore likely to be inconsistent with the economic objectives of ports. Hence, efficient time use may not be relevant for the EXPORT project, because we are emphasizing the ports' private costs (based on their assumed economic objectives).

There is, however, a question about whether we should treat the time used to load/unload ships as an input to the cargo handling process. This seems like a plausible assumption, because one may expect that other relevant inputs (i.e., capital and labor) are substitutes for the time use. That is, by acquiring more labor or equipment, the time to load/unload a given amount of cargo may decrease.

[22] The same argument applies to trucks' time spent in port area, i.e., the gate-to-gate time for trucks, which also produce external costs if engines are running. However, there are no comprehensive data source on trucks' activities in ports in Norway. Note that since the current estimates on air pollution and noise emissions from road transport (Thune-Larsen et al. 2014) are based on activity data, not on fuel consumption, adding trucks' emissions taking place on the port's premises should in principle not lead to double counting of external costs.

[23] However, prolonged loading/unloading could also be a question of sub-optimal organization or capacity utilization.

7.4 How should we select decision-making units?

There are 125 ports in Norway (excluding Svalbard). They do not form a group of homogenous and thus comparable decision-making units, and we must evaluate a wide range of criterions for appropriate sample selection. We propose the following guidelines:

- **Selection by geography:** Ports located in the same area are likely to be connected to the same hinterland, and may be influenced by the same contextual variables
- **Selection by cargo type or types:** A typical example would be to only consider container ports as in Schøyen and Odeck (2013). On the other hand, containerized cargo account for only a minor share of the overall cargo handled by Norwegian ports, and the comparison of more common cargo types may be more important. Emphasizing one cargo type does not acknowledge ports as multi-output producers, and does not allow identifying economies of scope in handling multiple cargos.
- **Selection by port size:** The size of the port is positively related to the degree of specialization in handling different types of cargo (Jara-Diaz et al., 2006)
- **Selection by corporate structure:** Local government, Cooperation between local governments, government owned corporation, private enterprise
- **Selection by ownership category:** Public Operating Port, mixed ownership port, public landlord port, non-government port (Cheon et al., 2010)
- **Selection by type of port:** E.g., industrial ports, traffic ports, governmental fishery ports
- **Selection by appointment:** The Norwegian Coastal Administration classifies 32 ports as trunk line ports (stamnetthavner), while the remaining ports are consider local ports whose main priority is to serve local communities

8 Guidelines for future research

Section 7 discussed some of the most important findings of the report. Based on this section, we will now provide some suggestions for future research. This task includes proposing relevant modeling and data collection strategies. As stated in Section 2, the main objectives of the EXPORT-project is to provide decision makers and other stakeholders with new knowledge on port efficiency in Norway, aiming to optimize the exploitation of the infrastructure and increasing the attractiveness of maritime transport. In other words, to provide empirical research that identifies and explains best practices in port operations.

8.1 Research in traditional port economics

The EXPORT-project will, to some extent, follow along the lines of port economics, using production analysis. However, we aim to provide more richness to this research by modelling ports as multi-output production and exploring both economies of both scale and scope. Our literature review showed that the amount of research on these aspects is relatively scarce, and non-existing in a Norwegian context.

In order to capture more of the complexity in port production than most other terminal studies, we aim to obtain panel data for a set of comparable Norwegian ports. In order to provide maximum relevance to decision makers and stakeholders, we will utilize as recent data as possible. Data from Statistics Norway, annual reports, BOF-register, and Proff Forvalt that we have discussed previously in this report, are currently available up to 2013. During the course of the EXPORT-project, we might even be able to get data for 2014.

As mentioned earlier, the available data from the various sources will have gaps and overlaps. In order to verify and/or fill the gaps in the available data, it might be necessary to contact agents engaged in port activities and/or conduct a survey. If we choose to conduct a survey, both the development and piloting of the survey will be undertaken in cooperation with one or two ports. This will help us find a realistic scope for gathering data that is not already available.

8.2 Research in environmental port economics

As our literature review showed, there have been relatively few production analyses that include external costs in the port economics literature. Our study aim to provide more richness to this branch of research. In Section 7, we pointed out that sub-sea pollution dispersion and emissions to air from ships may be relevant externalities to consider, along with noise, air pollution emissions and accidental spills during land-based cargo handling. We feel that that these externalities are related to different stages of port operations, and are therefore to a certain degree separable. Exploiting the separability property, we are able to model the different externalities using multiple connected models rather than one large production model. This will act as a remedy of potential "degrees of freedom" problems, and can also be helpful for optimal exploitation of the available data.

8.2.1 Turbidity

Turbidity is by far the simplest case to handle, because it is primarily dependent on the number of ships leaving and entering the ports, and to some extent ship size relative to sea depth (Klima og Forurensingsdirektoratet, 2011). This information can easily be obtained from the port statistics. Information about turbidity and other contextual conditions (e.g., sea depth, sediment characteristics) can be obtained from the Norwegian Environment Agency. We propose the following model for turbidity, which is defined based on Ragnar Frisch's (1965) multi-ware production model:

Cargo thoughput = f(the number of ship calls)

Turbidity = g(the number of ship calls; contextual variables)

This modelling approach includes jointly estimating two production functions; one for cargo throughput as a function of the number of ship calls and one for turbidity. Assuming the usual properties of production functions, cargo throughput and turbidity increase in the number of ship calls. Thus, the production model readily allows calculating the contribution of a marginal ship call to turbidity, and thus marginal turbidity costs (assuming that unit prices for turbidity are available).

Note that the cargo throughput is only a function of the number of ship calls (number of ships over a certain size), and not the ports' input use to handle the cargo. Thus, this production relation does not provide a suitable measure of managerial efficiency for ports, but an estimate of the exploitation of the carrying capacity of ships. Although this is a different definition of efficiency (one which is likely to be outside of the control of port managers), we believe that it would be useful to examine differences in average ship size and throughput per ship across ports. Our modelling strategy paves the way for an alternative definition of economies of scale for ports, compared to the common definition in the literature. It could have implications for making the ports' fee and pricing scheme socio-economically optimal.

8.2.2 Air pollution emissions from ships' engines

Air pollution emissions from ships' engines whilst berthed depend on the type of auxiliary engines in use and their overall load and energy consumption (e.g., NOX emissions are non-linear to utilized percentage of engine load). This can, in turn, be related to the time spent on loading and unloading ships. Information about the time used to load and unload cargo can be obtained from Statistics Norway's port statistics, while information about auxiliary machinery details per individual ship might be obtained from IHS Fairplay World Register of Ships. For literature on challenges on auxiliary engine performance data collection and estimates, se Buhaug et al. (2009) for more information.

Assume a multi-ware production model consisting of the following two production relations:

Cargo handled by the port
= f(time spent on loading/unloading cargo, capital stock, labor)

Air pollution emissions from ships at berth
= g(time spent on loading/unloading cargo, ship energy consumption; ship engine type)

The first production function relates the amount of cargo loaded and unloaded to the time use and to the ports' use of capital and labor. Assuming standard properties of the production function, increasing the capital and labor stocks allow handling a greater amount of cargo using less time than before the factor augmentation.

The second relationship relates the ship's air pollution emissions at berth to the time spent on loading and unloading cargo. The time-use is clearly positively related to air pollution emitted at berth. Hence, our two-equation production system readily allow us to model the relationship between the port's efficiency and its use of capital and labor, and the ships' air pollution emissions at berth.

8.2.3 Noise and air pollution from land-based port operations

Noise and air pollution emissions due to port operations depend on the *use* of equipment such as cranes and conveyor belts. Air pollution emissions such as CO_2 depend largely on the fuel consumption. As previously explained, air pollution and noise emissions are often calculated based on emissions factors that can be obtained from a variety of sources. Using emission factors to calculate emissions is also consistent with recent developments in the production analysis literature on bad outputs; see Section 5.7. We are therefore in favour of following this approach, and overall to defining port technology in the following way:

$$T=\left\{ \begin{array}{l} \left(\text{capital, labor, energy, cargo throughput, noise, air pollution}\right): \\ \left(\text{capital, labor, energy,}\right) \text{ can produce } \left(\text{cargo throughput, noise, air pollution}\right) \end{array} \right\}$$

This is a very general representation of the technology, which also encompasses the technology specification comprising cargo-specific technologies with specialized inputs that was proposed in Section 4.1.3.1.

8.2.4 Emissions to sea and soil

We conclude the report by suggesting a simple approach to examine accidental spills to sea and soil, building on Just and Pope's (1978) seminal approach to modelling production risk. Their approach comprises a two-stage analysis, in which a stochastic representation of the technology is estimated in the first stage, and a second-stage regression is thereafter executed to explain the error term variance of the first-stage regression.

We consider the Norwegian Costal Administration's weekly reports on oil spills to be a viable source of data on accidental spills. Utilizing the idea of Just and Pope, we can define a stochastic function explaining accidental spills by the port operations technology from section 8.3, and an error term (e) which can be thought of as an manifestation of production risk:

Accidental spills = f(capital, labor, energy, cargo throughput) + e

The following modelling strategy can be considered:

i) Estimate the regression equation and predict the error term, e
ii) Identify variables that are expected to increase or decrease the probability of accidental spills taking place by a priori reasoning
iii) Run a regression where the identified variables are used to explain the variations of e (the error term)

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10 Appendix

10.1 Literature review summary tables Port Economics

10.1.1 Externalities excluded

Port Economics category	Theme	Author and year	Title	Variables	Data source
Terminal studies (overlaps also with Port Governance and Port Competitive-ness)	Operational efficiency Port competitive-ness	Jose Tongzon, Wu Heng 2005	Port privatization, efficiency and competitiveness: Some empirical evidence from container ports (terminals)	Operational efficiency Yi the total throughput in TEU on container port (terminal) i; X1i the terminal quay length in meters of port i; X2i the terminal surface in hectares of port i; X3i the number of container quay cranes used on port i; Z1i the size of port i, which is the dummy variable to distinguish whether the total annual throughput of the observation exceeds one million TEUs or not; Z2i the extent of the private sector participation in port (terminal) i; Port competitiveness Xi1 efficiency level for port i;	Containerization International Yearbook Survey of shipping lines (i.e. ports customers)

Port Economics category	Theme	Author and year	Title	Variables	Data source
				Xi2 cargo handling charges of port i; (was unavailable) Xi3 reliability of port i (delayed time); (was unavailable) Xi4 the number of direct-call liner services; Xi5 the depth of the navigation channel of port i; Xi6 adaptability to the changing market environment of port i; Xi7 landside accessibility of port i; Xi8 products differentiation of port i (investment in marketing) (unavailable)	
Terminal studies	Operational efficiency	Tongzon, J., 2001.	Efficiency measurement of selected Australian and other international ports using data envelopment analysis.	TEUs handled (output) Shipcalls (number of ship visits) (output) Shiprate (ship working rate which measures the number of containers moved per working hour per ship) (output) Crane productivity (measures the number of containers moved per crane per working Hour) No. of cranes No. of container berths No. of tugs Terminal area (m2) Delay time (h) (difference between total berth time plus time waiting to berth and the time between start and finish of ship working)	Sources: Australian Bureau of Transport and Communications Economics, Waterline, Issues No. 6 & 7, March & June 1996; Containerization International Yearbook (1998); LloydÕs Ports of the World (1998).

Port Economics category	Theme	Author and year	Title	Variables	Data source
				Labor (units) (number of port authority employees.)	
Terminal studies	Operational efficiency Comparison between DEA and SFA	Kevin Cullinane et. al. 2006	The technical efficiency of container ports: Comparing data envelopment analysis and stochastic frontier analysis	Container throughput (TEU) Terminal length (m) Terminal area (ha) Quayside gantry cranes (number) Yard gantry cranes (number) Straddle carrier (number)	Containerization International Yearbook and Lloyd's Ports of the World
Terminal outputs		V. F. Valentine and R. Gray (2001)	The measurement of port efficiency using Data Envelopment Analysis	Containers (output) Total throughput (output) US$- Assets Quayage (m) Their results merely show that the ports can be ranked in order to show which ports achieve a greater throughput with the minimum of assets and least berth space, i.e. quayage. In order to achieve an absolute efficiency rating additional data needs to be included within the equation. Such additional data would have to include all the port's outputs such as number of passengers; amount of general, liquid, bulk or other type of cargo that pass through the port as well as other inputs, such as number of employees or cranes utilised.	Cargo Systems Journal 1999 list of top 100 container ports
Terminal studies	Operational efficiency	Cullinane, K.P.B., Song, D.-	A stochastic frontier model of the efficiency	Y - terminal output as measured by annual container throughput in TEUs.	Containerization International Yearbook (various

Port Economics category	Theme	Author and year	Title	Variables	Data source
		W., Gray, R., 2002	of major container terminals in Asia: assessing the influence of administrative and ownership structures.	X1 - terminal quay length in metres. X2 - terminal area in hectares. X3 is defined as the number of pieces of cargo handling equipment employed; gantry cranes, ship-shore gantries, yard cranes, and mobile cranes etc.	issues) also validated and, in certain instances supplemented, by terminals themselves
Terminal studies	Operational efficiency	Coto-Millan, P., Banos-Pino, J., Rodriguez-Alvarez, A., 2000	Economic efficiency in Spanish ports: some empirical evidence	Production variable: aggregated port activity, the total of goods moved in the port in thousands of tonnes, the passengers embarked and disembarked and the number of vehicles with passengers. Three variable inputs are incorporated: labor (L), capital (K) and intermediate consumptions (E). Prices are obtained as follows: the price of labor wL is the ratio of total employee costs to the total number of workers employed. The price of capital wK is obtained by dividing the depreciation of the period by the number of linear metres of the quays with depth greater than 4m. The price of intermediate consumption wE is the ratio of consumption, external supplies, services costs and other expenditure to the port activity (measured in tonnes).	Spanish Ministry of Transport
Terminal studies	Operational efficiency	Cullinane, K.P.B., Song, D.-W., 2003	A stochastic frontier model of the productive efficiency of Korean	Terminal output (Y) is defined as the turnover derived from the provision of container terminal services but excluding property sales Labor inputs: (L1) total remuneration of directors or executives for their managerial services. (L2) total wages and salaries paid to employees.	Korea Container Terminal Authority Annual reports and financial accounts published by each of

Port Economics category	Theme	Author and year	Title	Variables	Data source
			container terminals	Capital inputs: (K1) net book value of fixed equipment, buildings and land utilized for the purpose of terminal operations. (K2) net book value of mobile and cargo handling equipment including container cranes, yard tractors and fork lifts.	the five container terminals in UK
Terminal studies	Operational efficiency	Bingliang Song, Yuanyuan Cui 2014	Productivity changes in Chinese Container Terminals 2006–2011	Throughput (1000TEU) (output) Staff and workers(No.) Bridge cranes (No.) Quay length (m)	China's PortYearbooks2007–2012
Terminal studies	Operational efficiency (with Malmquist)	Yuen et al. (2013)		Output: Container throughput (TEU) (1) Number of berths (2) Total berth length (m) (3) Portland area (m2) (4) Number of quay cranes (5) Number of yard gantries	
Terminal studies	Operational efficiency (with Malmquist)	Cheon et al. (2010)	Evaluating impacts of institutional reforms on port efficiency changes: Ownership, corporate	Output: Container throughput (TEU) (1) Berth length (m) (2) Terminal area (m2) (3) Container crane capacity (tonnage) (The article makes interesting points about labor input)	3 sources: Containerisation International-Online, CIY, Ports and Terminals Guide (Lloyd's Register Fairplay- to confirm the data and take

Port Economics category	Theme	Author and year	Title	Variables	Data source
			structure, and total factor productivity changes of world container ports		into account different container handling practices)
Terminal studies	Operational efficiency (with Malmquist)	Alejandro and César (2009)	Mexico: total productivity changes at the principal container ports	Output: Container cargo handled (1) Storage area (m2) (2) Length of docks (m) (3) Gantry cranes (number)	
Terminal studies	Operational efficiency (with Malmquist)	Liu et al. (2008)	The efficiency of container terminals in mainland China: an application of DEA approach	Output: Container throughput (TEU) (1) Quay length (m) (2) Quayside gantry crane (number) (3) Rubber-tyred gantry crane (number)	
Terminal studies	Operational efficiency (with Malmquist)	Estache et al.(2004)	Sources of efficiency gains in port reform: a DEA decomposition of a Malmquist TFP index for Mexico.	Output: Volume of merchandise handled (tonnes, all types of mercandise) (1) Capital: Length of docks (m) (2) Labor: Number of workers	

Port Economics category	Theme	Author and year	Title	Variables	Data source
Terminal studies	Operational efficiency (with Malmquist)	Schøyen and Odeck (2013)	The technical efficiency of Norwegian container ports: A comparison to some Nordic and UK container ports using Data Envelopment Analysis (DEA).	Output: Container throughput (TEU) (1) Berth length (m) (2) Terminal area (m2) (3) Number of yard gantries (4) Number of straddle carriers (5) Container handling trucks Assumption: A fixed relationship between labor and terminal facilities	Data from Containerisation International Yearbooks were presented to each of the 24 port authorities for "cleaning" before DEA was conducted
Terminal studies	Operational efficiency (with Malmquist – where congestion efficiency is included)	Simoes, P. and Marques, R. C., 2010a	Influence of congestion efficiency on the European seaports performance: Does it matter?	Outputs: General cargo (tons), Ro-Ro cargo (tons), dry bulk cargo (tons), liquid bulk cargo (tons) and passengers (number) Inputs: Operational expenditure (OPEX) and capital expenditure (CAPEX)	Sea Ports Annual Reports (supplemented with EUROSTAT)
Terminal studies	Operational efficiency (with Malmquist)	Simoes et al. (2010)	Governance and comparative performance of Iberian Peninsula seaports: An application of nonparametric techniques	Outputs: General cargo (tons), Ro-Ro cargo (tons), dry bulk cargo (tons), liquid bulk cargo (tons), containers (TEU) and passengers (number) Inputs: Quay length (m), employees (number), cranes (number)	

Port Economics category	Theme	Author and year	Title	Variables	Data source
Terminal studies	Operational efficiency (FDH; order-m DEA efficiency)	Simoes and Marques (2010 b)	Seaport performance analysis using robust nonparametric efficiency estimators.	Outputs: Dry bulk cargo (tons), liquid bulk cargo (tons), containers (TEU) and passengers (number) Inputs: Sum of Operational expenditure (OPEX) and capital expenditure (CAPEX) to Total Operating Expenditure (TOPEX)	Sea Ports Annual Reports (supplemented with EUROSTAT)
Terminal studies	Operational efficiency (with Malmquist)	Barros (2011).	Productivity analysis of Brazilian seaports	Outputs: Dry bulk cargo (tons), liquid bulk cargo (tons), containers (TEU) Inputs: Quay length (m), employees (number), cranes (number)	1) data obtained from the website of ANTAQ, 2) directly from ports, and 3) from the book Terminais Marı´timos e Portos Brasileiros
Terminal studies	Operational efficiency (with Malmquist)	Cullinane and Wang (2010)	The efficiency analysis of container port production using DEA panel data approaches	Output: Container throughput (TEU) (1) Berth length (m) (2) Terminal area (ha) (3) Number of quayside gantries (4) Number of yard gantries (5) Number of straddle carriers	Containerisation International Yearbook and Lloyd's Ports of the World
Terminal studies	Operational efficiency	Munisamy and Singh (2011)	Benchmarking the efficiency of Asian container ports	Output: Container throughput (TEU) (1) Berth length (m), (2) Terminal area (ha), (3) Total number of refer points,	Containerisation International Yearbook 2007

Port Economics category	Theme	Author and year	Title	Variables	Data source
				(4) Number of quayside cranes, (5) Total number of yard equipment According to Notteboom et al. (2000), expert analysis shows that there is a stable relationship between the number of yard gantries with the number of dock workers. Wang et al. (2005) goes to show that the average number of workers per crane is six. Hence, we take the total yard equipments, i.e. sum of straddle carriers, yard gantries, reach-stackers, front-end handlers, and forklifts, as an input factor, reflecting the labor that is required.	

10.1.2 Externalities included

Port Economics category	Theme	Author and year	Title	Variables	Data source
Terminal studies (overlaps with Port Policy and regulation)	Environ-mental impact analysis	Ingrid Mateo-Mantecón et al. (2011)	Measurement of the Ecological and Carbon Footprint in Port Authorities	Data used to construct Corporate Ecological Footprint and Corporate Carbon Footprint: Financial data from ports Consumption (electricity, fuel, paper, water) data from ports	Participating port's finance department
Terminal/ port studies	Environ-mental efficiency	Chang, Y.T.,2013	Environmental efficiency of ports: a data envelopment analysis approach	Vessel (1000 tons) (good output) Cargo handled (1000 tons) (good output) CO2 emission (tons) (bad output) Labor (person) Quay length (m) Terminal area (m2) Energy consumption (TOE, Ton Oil Equivalents) They apply labor data because it was available, but exclude the number of handling equipment as the DMU in this study is the port and not the container terminal as done by the Cullinane team. Too many different types of handling equipment would be involved in the port level unlike more standardized container terminals if handling equipment were included. Therefore, any arbitrary counting of the equipment and decision on including and excluding the equipment among various types across ports is more likely to lead to biased results.	Korea Ministry of Land, Transport and Maritime Affairs (Statistical Yearbook, reports, database), report from KMI

Port Economics category	Theme	Author and year	Title	Variables	Data source
Terminal/ port studies	Environ-mental efficiency	Chin, Anthony T. H. and Joyce M. W. Low. 2010.	Port Performance in Asia: Does Production Efficiency Imply Environmental Efficiency?	Desirable output is annual container capacity flows between 13 ports (156 O–D pairs) Undesirable outputs are primarily gaseous emissions that include NOx, SO2, CO2 and particulate matter Two inputs are considered; the frequency of shipping services and bilateral trade flows	Capacity flows: AXS-Alphaliner Inter-port nautical distances : Searates Bilateral trade value: International Monetary Fund
Terminal studies	Energy usage and CO2 - emissions	Geerlings et al. (2010)	A new method for assessing CO2-footprints of container terminals in port areas	To calculate Wx = Total weight of CO2-emission produced at terminal x, the following variables are needed: Vi,j = Yearly consumption of diesel in litres with equipment i to modality j fD = Emission factor in kilogrammes of CO2-emission per lit diesel (= 2.65) Pi,j = Yearly power consumption of electricity in kWh for equipment i to modality j FE = Emission factor in kilogrammes of CO2-emission per kWh (= 0.52), ni,j = Number of rides with equipment i to modality j Ci,j = Fixed diesel consumption (for example lifting operations) per ride in litres	Data provided from terminals voluntarily

Port Economics category	Theme	Author and year	Title	Variables	Data source
				ci,j = Variable diesel consumption per km in litres (see Table 1) X i,j = Distance travelled (Manhattan-metric) for equipment i to modality j pi,j = Fixed usage per ride in KWh for equipment i to modality j Overview of possible combinations with different types of equipment (i) and the modalities (destinations) (j): 1 Quay Crane (QC) 2 Barge Crane (BC) 3 Rail Crane (RC) 4 Automated Stacking Crane (ASC) 5 Rail-Mounted Stacking Crane (RSC) 6 Platform (P) 7 Automated Guided Vehicle (AGV) 8 Straddle Carrier (SC) 9 Terminal Truck (TT) 10 Multi-Trailer System (MTS) 11 Reach Stacker (RS)	
Terminal studies	Environ-mental efficiency	Yang (2013)	Productivity changes in Taiwan's port	Revenue ($) (good output) DO-levels (dissolved oxygen) (bad output)	

Port Economics category	Theme	Author and year	Title	Variables	Data source
			industry incorporating environmental regulations on harbor water quality	Labor (person) Fixed assets ($) Expenses ($) Service population for each port (contextual varialble in order to control for favourable/unfavourable operating context)	

10.2 Literature review summary tables Economies of scale and scope

Port Economics category	Theme	Author and year	Title	Variables	Data source
Terminal studies	Economies of scale and scope	Jara-Diaz et al. (1997)	Marginal costs and scale economies in spanish ports	C(Y2,Y3,Y5,Y6,Y7, W1,W5,W6) Quadratic cost function: C(Y2,Y3,Y5,Y6,Y7, W1,W5,W6) C: Long term total annual cost (includes labor (GL), amortisation (GK) and other expenses (GI), directly obtained from port reports) Y2:Tons of non-containerized general cargo Y3: Tons of containerized general cargo. Y5: Tons of liquid bulks. Y6: Tons of dry bulks. Y7: Index added of other activities that use part of the infrastructure (An output representing other activities that induce expenses in infrastructure, i.e. space constructed by the port and rented to private firms. As there was no information available on the physical amount of space assigned for this purpose, the total rent received (CANON) was used as a proxy.) W1: Labor price (labor expenditure/number of employees) W5: Capital price (actual economic value of physical capital divided by the total dock length) W6: Intermediate input price (constructed as the ratio between the sum of consumption, services externally provided plus other expenses, and an index of total activities represented by annual revenue)	

Port Economics category	Theme	Author and year	Title	Variables	Data source
Terminal studies	Economies of scale and scope	Jara-Diaz et al. (2002)	Econometric estimation of scale and scope economies within the Port Sector: a review	Quadratic cost function: C(Y2,Y3,Y5,Y6,Y7, W1,W5,W6) C: Long term total annual cost (includes labor (GL), amortisation (GK) and other expenses (GI), directly obtained from port reports) Y2:Tons of non-containerized general cargo Y3: Tons of containerized general cargo. Y5: Tons of liquid bulks. Y6: Tons of dry bulks. Y7: Index added of other activities that use part of the infrastructure (An output representing other activities that induce expenses in infrastructure, i.e. space constructed by the port and rented to private firms. As there was no information available on the physical amount of space assigned for this purpose, the total rent received (CANON) was used as a proxy.) W1: Labor price (labor expenditure/number of employees) W5: Capital price. W6: Intermediate input price (constructed as the ratio between the sum of consumption, services externally provided plus other expenses, and an index of total activities represented by annual revenue) Di: Port-specific dummy variable Finally, the **capital price** was obtained as its actual economic value divided into the total dock length (drought larger than four meters) as a proxy for the amount of physical capital. The economic value of capital used within the period was calculated as the amortisation plus	Directly from the port authorties

Port Economics category	Theme	Author and year	Title	Variables	Data source
				six per cent (target social profit rate for the Spanish port system) of the net value of physical assets corresponding to infrastructure currently used for port services	
Terminal studies	Economies of scale and scope	Jara-Diaz et al. (2005)	Environmental efficiency of ports: a data envelopment analysis approach	Quadratic cost function: C(Y2,Y3,Y4,W2,W3, W4,W5,W6,W7,D3, T) C: Total monthly cost Y2:Tons of non-containerized general cargo Y3: Tons of containerized general cargo. Y4: Tons of Ro-Ro cargo for port i in year t. W2: Non-port worker personal price (labor expenditure/number of employees) W3: Ordinary port worker price (labor expenditure/number of employees) W4: Special port worker price (labor expenditure/number of employees) W5: Capital price (The ratio between the capital cost and the active capital of the period (net fixed assets under exploitation). W6: Intermediate input price (The price of electricity has been used as an indicator of the price of intermediate consumption) W7: Area input price (ratio between expenses and total area) Di: Firm-specific dummy variable T: Temporal trend.	Data directly from three firms operating within the port area of Las Palmas located in Gran Canaria

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Norwegian Centre for Transport Research

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