Benchmarking Sustainability Performance of Ports

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ABSTRACT

Sustainable development agendas are challenging the world and ports, in particular, to find ways to become more efficient while meeting economic, social and environmental objectives. Although there has been a considerable body of documentation on green port practices and performance in Europe and America, there is limited synthesis about evaluation of sustainable practices in the Canadian ports context. This research aims to provide a modeling framework for benchmarking the sustainability performance of ports and to identify targets for improvement.

A two-step approach is proposed. First, a review of literature and initiatives employed by global port authorities is conducted to identify major sustainability performance indicators. Second, data envelopment analysis (DEA) is applied to evaluate port performance while taking into account the dimensions of sustainable development. The DEA models evaluate both undesirable and desirable outputs for ports. Three categories of models are proposed namely; ignoring undesirable output, treating undesirable output as input, and directional distance function under variable and constant returns to scale. A case study for 13 North American ports is conducted. The results indicate that performance evaluations vary with economic and social criteria. The indicators and methodology undertaken can be used by ports and other industrial service sectors for improving green performance.

Keywords: Ports; Sustainability Measurement; Performance Analysis; Benchmarking; Data Envelopment Analysis

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Glossary

CRS	Constant returns to scale
DEA	Data Envelopment Analysis
GHG	Greenhouse gases
LNG	Liquefied and Natural Gas
PM	Particulate matter
SE	Scale efficiency
SFA	Stochastic Frontier Analysis
SWOT	Strength Weakness Opportunities and Threats
TE	Technical efficiency
TEU	Twenty-foot Equivalent Unit
VRS	Variable returns to scale

Chapter 1

Introduction

1.1 Background

Sustainable development agendas are challenging ports and the world in general to find ways to become more efficient while meeting economic and social objectives. North American ports' goal to mitigate environmental footprint aligns with some initiatives undertaken by global ports in various forms, which are in relation to global sustainable development.

The Sustainable Development Goals (SDGs) released at the United Nations Conference, Rio+20 in 2012 defined universal targets to meet the urgent environmental, political, economic and social challenges facing the world. As an evolution of the Millennium Development Goals (MDGs), SDGs 17 goals deal with issues ranging from climate change threats and how we manage our fragile natural resources to better health which helps to eradicate poverty and foster peace and inclusive society. Coincidentally, the SDGs are backed with other global agreements like the Paris Climate Conference (2015) and the Sendai Framework for Disaster Risk Reduction (2015) with a focus to reduce the carbon emissions, manage the risk of climate change and build back after a crisis.

These goals affect every vertical in an economy, and the port is not excluded from this. Ports are commercial infrastructures that form part of the most critical assets of national economies. In 2014, The American Association of Port Authorities reported that seaport activities account for 26% of the U.S. economy which translates to over 23 million jobs in the country. Similarly, containerization has significantly reduced the transportation cost of international trade and increased labor productivity. An example to buttress that is the fact that before containerization, fewer goods were transported across the globe but in the present day, a European brand product can be designed in North America and manufactured in Asia because of the transportation effectiveness. The importance of ports cannot be undermined.

Although ports are a vital part to the engine of an economy, they are also locations that harbor environmental and social pollution originating from land, ships and port machinery activities (Roh et al., 2016). This has led to the provision of sustainable development policies/legislation for ports both globally and locally that aim to incorporate environmental issues into core strategies and operations of port development. From a strategic viewpoint, some of legislation can be seen in the European Union (Classification Societies – Regulation(EC) No 391/2009, Ship-Source Pollution – Directive 2000/59/EC, Marine Equipment – Directive 96/98/EC and Directive 2014/90/EU), Australia (Environmental Protection Act 1986), New Zealand (Resource Management Marine Pollution Regulations), United States of America (Diesel Emission Reduction Act), and Singapore (Environmental Protection and Management Act (Cap.94A). In addition to the strategic perspective, there is a need for the operations vertical to be adequately managed to cope with the limited environmental resources to meet up with growing interactions. Some work has been done in this respect for some areas of the world; however, very few have been considered from a North American perspective.

1.2 Problem Statement/ Thesis Objective

In 2010, the Port of Montreal adopted its first sustainable development policy and revised it in 2016 to address the evolving challenges in sustainable development and the expectation of stakeholders. The policy is based on six guiding principles as follows; ensure the responsible management of the organization, contribute to the prosperity of society, provide a stimulating work environment, reduce the environmental footprint, ensure that safety and security remain core operating values and ensure the Port of Montreal's economic mission (Port of Montreal, 2010).

The Green Harbor Trucking Initiative is one of the key mandates of the revised policy. The initiative, centered on reduction of truck-related greenhouse gas, addresses three core areas; GHG inventory management, monitoring and optimization of truck transaction through technology, and growing unrest in harbor trucking. With a priority to reduce the environmental footprint of activities through responsible consumption and efficient managing of environmental resources, only few studies have assessed the port's performance with counterparts in the industry with similar values and cultures. Moreover, the focus has been largely on internal benchmarking. This study is motivated by the Green Harbor Trucking Initiative at the Port of Montreal and addresses benchmarking of port sustainability performance. The research will help understand how North American ports can improve from a sustainable development perspective. The thesis has three main objectives:

a. Review the literature on port sustainability measurement.
b. Determine methodology and models for port sustainability performance measurement and the evaluation criteria.
c. Conduct a case study in North American context and validate model performance.

1.3 Thesis Contribution

This study allows us to benchmark port sustainability performance and identify best practices specific to the region. In other words, detect peers or dominating ports that can serve as a reference to other ports, practices that are likely to provide a higher performance boost if fulfilled. These objectives are addressed from a quantitative and qualitative perspective by evaluating the technical and scale efficiencies using DEA, performing a strength, weakness, opportunity and threat

(SWOT) analysis and examining the variables that most impact sustainability development. The proposed DEA models evaluate both undesirable and desirable outputs for ports. Three categories of models are proposed namely; ignoring undesirable output, treating undesirable output as input, and directional distance function under variable and constant returns to scale. A case study for 13 North American ports is conducted.

1.4 Organization of Thesis

The structure of the thesis is outlined as follows:

Chapter 2 reviews sustainability initiatives taken by North American ports, methods for ports sustainability performance measurement, and benchmarking.

Chapter 3 describes the solution approach. We specify the DEA models used, inputs and outputs variables, the data collection methods, and criteria employed in this study. The calculation of technical and scale efficiency is also demonstrated.

Chapter 4 applies the proposed DEA variants to determine the efficiency of the container ports via a case study.

In chapter 5, we conclude the thesis and outline directions for future works.

Chapter 2

Literature Review

2.1. Introduction

Research has shown the damaging effects environmental pollution has on humans and the Earth at large (World Commission on Environment and Development, 1987, p.8.). This has brought awareness to the term ‘sustainable development’ which was coined by the World Commission on Environment and Development also known as the Brundtland Commission. The commission defined sustainable development as “the one that meets the needs of the present without compromising the need of future generations” (UN 1987, p.43). Another definition from the American Association of Port Authorities (AAPA) is given as "sustainability involves the simultaneous pursuit of economic prosperity, environmental quality, and social responsibility." Therefore, organizations at different levels and in different industries are incorporating sustainability initiatives into their strategic and operational conduct. Following this thought pattern, Bonney (2007), Dante (2003), Gibb (1997), Houstan and Steinberg (2008), Guiliano et al (2008), Forstner and Heise (2006) Wang & Chang (2012), Walker (2016), and (Davarzani et al, 2017) started looking into ports and the umbrella industry for potential directional path to mitigate the adverse effects of environmental pollution.

In this chapter, we review the underlying theories that serve as the fundamental for this research. The chapter is divided into three sections. First, we review the sustainability initiatives undertaken by ports. Second, we examine the criteria and methods for benchmarking analysis, their advantages, disadvantages, and finally, we identify the research gaps with respect to container ports from an operations and ecological standpoint.

2.2. Ports Sustainability Practices

Port sustainability has three primary dimensions; environmental quality, economic prosperity, and social responsibility (Cheon and Deakin, 2010), which implies the need to navigate the balance between multiple variables such as coastal stewardess, communities, and facilitators of economic and logistics imperatives (Goulielmos 2000). Beyond compromising the ecological balance, ports and respective stakeholders are implementing sustainability initiatives to strengthen their brand as a form of competitive advantage in the industry they operate in (Galbraith et al., 2008).

To get a better understanding of the situation, we examined some of the sustainability practices initiated by North American and European ports through review of literature, journals, and port authority online platforms. The champion ports that were considered are: Port of Los Angeles (USA), Port of Long Beach (USA), Port of Oakland (USA), Port of New York-New Jersey (USA), Port of Montreal (Canada), Port of Vancouver (Canada), Port of Rotterdam (Netherlands), and Port of Antwerp (Belgium). A summary of their sustainability initiatives is shown in Table 1.

2.2.1. Port of Los Angeles and Port of Long Beach

Port of Los Angeles (POLA) and Port of Long Beach (POLB) are the twin economic engines that process nearly 40% of the container cargo that comes to the United States. Both ports generate about $400 billion of economic activity every year and facilitate one out of every nine jobs in the Southern California region. POLA recorded 8.8million twenty-foot equivalent unit (TEUs) in 2016. Similarly, POLB serves 175 shipping lines and connects to 217 ports globally. In 2017, the port recorded its busiest period in a century with over 7.5 million container units.

Both ports are landlord ports committed to sustainability and are aggressive with green initiatives, (POLA, 2018; POLB, 2018). The trucking activities operating in POLA and POLB has negatively impacted the community through substantial air pollution and other impacts. Studies by the South Coast Air Quality Management District (AQMD) and the California Air Resources Board (CARB) concluded that more than two million people who live near the POLA and POLB face higher health risks than those who live elsewhere in the region. To address the air pollution issues, the ports developed clean truck programs (CTP), which are a part of their broader sustainability initiative with the primary objective to reduce harmful emissions from heavy-duty trucks transporting through the ports. The implementation of these strategies did not go smoothly without facing some challenges; push backs, lawsuits by the American Trucking Association alleging anti-competitiveness (ARB, 2012) and losing partner trust due to the breakdown of the encouraged liquefied and natural gas (LNG) trucks ("How The Local Ports Reduce Pollution," 2017). However, the CTP was successful with the ports delivering an estimated 80% reduction in the rate of truck emissions compared to 2007 average air emissions even as they experienced an increase in trade volume, which has also helped to reduce the health impact costs.

Ships are usually the most significant contributor to adversely impacting sustainability. Some programs have been rolled to optimize these effects. POLA and POLB adopted three core programs; green ship incentive index, vessel speed reduction and alternative maritime power (AMP). The green ship incentive program's goal is to reduce smog by rewarding ships with environmentally friendly engines. For instance, as stated on POLB website, vessels with engines meeting Tier 2 standards established by the International Maritime Organization (IMO) get a $2,500 incentive per ship call and those meeting Tier 3 get a $6,000 per ship call. The second program; vessel speed reduction program objective is to slow the speed of ocean-going vessels (OGV) within 20 nautical miles from the port (Linder, 2017). This way less NOx gas is emitted. The alternative maritime power aids in reducing emissions by having the ships plug into shore-side electrical power as opposed to operating on diesel power while at berth. In 2017, POLA and POLB reached a 70% reduction of the emission per power at berth for container ships when compared to baseline. Also, the ports' plan includes measures to reduce locomotive emissions through regulations, funding of clean technology, and enforceable agreements, e.g., limiting idling by trains to 15 minutes. Old diesel equipment were upgraded to zero-emissions, and in the case of those that could not be upgraded, they were replaced and monitored annually and maintained when necessary.

The California Air Resources Board (ARB) highlighted that harbor craft emissions are the third highest contributor of diesel particulate matter (PM). Initiatives implemented by POLA and POLB range from having the crafts fuel their engines with California ultra-low sulfur diesel and install a non-resettable hour meter on each engine. The projected result of this initiative is that by 2025, PM and NOx emissions will be reduced by 75% and 60% respectively. Furthermore, to maintain good water quality, POLB started a Port-wide Storm Water Pollution Prevention Control to put in place measures in crucial areas (Ueda et al., 2007). POLB's strategy was divided into two aspects; short and long-term. The short-term measures include general clean-up, i.e., sandbags, rock barriers as prevention of surface water pollution run-off while the long-term measures range from sustainable technology in accordance with California Regional Water Quality Control Board and data gathering of pollution sources. Finally, advanced green power whereby the port is powered by solar, wind, and geothermal are some of the energy initiatives deployed at the ports.

2.2.2. Port of New York-New Jersey

Port of New York and New Jersey (PNYNJ) is the third-largest port in North America. In 2016 the port processed 6.2 million TEUs valued at approximately $200 billion. This trade volume has established the port as the largest on the East Coast and capturing 30% of the market share.

PNYNJ primary strategy was to reduce dependency on trucking and increase efficiency through an appointment system. Although a clean truck program was implemented to address emissions from drayage trucks with the goal of phasing out the oldest trucks first, it was an action in the Clean Air Strategy. There are three primary implementation steps the port rolled out. First is the Truck Replacement Program. It is a toned-down version of the Port of Los Angeles program whereby trucks older than 17 years are not granted access to the port facility. Second is the new ship to rail facility. This initiative will provide significant environmental benefits including reduction in vehicle travel time, fuel consumption and a reduction in air emission. Lastly, appointment scheduling system that levels out peaks and valleys of truck arrivals. This reduced turn time by 46% in 2017 (Green Tech, 2017). The projected result of these initiatives is 1.6 million tonnes of CO2 avoidance over a period of 30 years, saving 142 million gallons of diesel, and avoidance of 17 million truck trips on local roads.

2.2.3. Port of Oakland

Port of Oakland is one of the top five container ports in the United States and primary node for Northern California's maritime trade. Over the last 16 years the number of TEUs processed has grown by 50%, and in 2017, the port recorded container traffic of 2.4 million TEUs. Port of Oakland is also committed to reducing its environmental footprint. This is shown by the multiple awards such as the 2003 Governor's Environmental and Economic Leadership Award by the California Environmental Protection Agency.

According to a research conducted by Berkeley scientist Robert Harley, Port of Oakland emissions of black carbon, a key component of diesel particulate matter and a pollutant linked to global warming, was slashed by 76 percent from 2009 to 2013. Emission of nitrogen oxides, which leads to smog, declined 53 percent. The median age of truck engines also declined from 11 to 6 years, and the percentage of trucks equipped with diesel particulate filters experienced an increase from 2 percent to 99 percent. With respect to shipping, Port of Oakland has a similar approach to POLA and POLB by implementing the shore power for OGVs at berth.

Environmental restoration is an integral part of sustainability. The port of Oakland donated 71.5 acres of land for construction of wetland restoration. The port also worked with other relevant stakeholders to develop an ecological reserve which provides habitat for various species to maintain the necessary balance (crabs, perch fish, etc.).

2.2.4. Port of Vancouver

The Port of Vancouver is located on the southwest coast of British Columbia. It is the largest in Canada with transactions valued at $200 billion in 2017. The port prides itself on sustainability initiatives and was the first port in Canada to implement stringent environmental requirements to reduce air emissions.

To address air pollution from trucking, the port introduced an initiative called the smart fleet, a three-year action plan to achieve excellence in the drayage sector. The initiative includes a global positioning system that allows the port authority to track and report on the turn and wait times. All drayage trucks are outfitted with GPS technology, a single reservation system which connects trucking companies to all container terminal operations for improved efficiency through reservation selection, increased gate operations hours to ease congestion and trucking licensing system. This enables all container trucking companies and their trucks meet specific criteria to gain access to the port facilities such as mandatory opacity testing, minimum truck age and idling reduction whereby all trucks are not allowed to go 3 continuous minutes in any 60-minute while on port property (Port of Vancouver, 2015).In 2014, Port of Vancouver recorded 20% reduction in truck turn times through the implementation of these initiatives.

Regarding shipping, Port of Vancouver installed shore power and invested in improving OGVs efficiency through an initiative called the container vessel on-time incentive program which allows discounted wharfage fees to vessels that are on time and the ecoaction program which offers discounts on harbor dues for meeting best practices that reduce emissions and environmental impacts. A pilot project to track all cargo through the train channel was launched. The objective was to collect informed decision that can improve the overall supply chain efficiency. Similar to Port of Oakland, in September 2016, the Port of Vancouver started construction to restore coastal wetland habitat. The Enhancing Cetacean Habitat and Observation (ECHO) program was also launched to mitigate the threat to the marine mammals especially for whales by reducing vessel noise and collecting of relevant data. Guidelines and policies to prevent water pollution caused by port tenants were developed and the ports established initiatives aimed at cost-effective alternative fueling options and improvement of energy-related operational efficiencies.

2.2.5. Port of Montreal

The Port of Montreal is the second largest container port in Canada and the only container port on the Quebec-Ontario corridor. Goods values at $41 billion move through the port on annual basis and in 2016, it was recorded that the port processed 1.44 million TEUs. The port is an advocate for sustainability and is a member of the Green Marine and Green Award program since 2009.

The Port of Montreal is guided by six sustainable development principles i.e. ensure the responsible management of the organization, contribute to the prosperity of society, provide a stimulating work environment, reduce the environmental footprint, ensure that safety and security remain core operating values and ensure the port's economic mission. Highlighting ten priority challenges to address, the port's orientation to tackle these challenges over a three year span are: to improve air and water quality, enhance the port authority's service, ensure the appropriate infrastructure and resources, offer a safe working environment and build relationships with relevant stakeholders. Some of the initiatives implemented are launching a new truck PORTal, incorporating RFID and license plate readers to optimize trucking operations, provision of electric shore power services for ships, hydrodynamic separators to treat storm water, affiliation with credible sustainability organizations to share resources, use of recycled materials at terminals.

2.2.6. Port of Rotterdam

Port of Rotterdam (PoR) is considered the largest port in Europe with a 37.5% market share. PoR is a landlord port that leases out its real estate to related businesses (Paipai 1999) and in 2016, moved 12.3 million container TEUs through its operations (PoR 2017). From a sustainability perspective, PoR is considered at the forefront of environmental advocacy.

In Europe, Port of Rotterdam has a shipping discount initiative similar to that of Vancouver. TO address the pollution from cargo-handling equipment, Port of Rotterdam intends to capture and store the CO2 generated from these machinery in empty gas fields under the North Sea, so it does not get into the atmosphere (PoR, 2016). This is a revolutionary initiative in the port industry. Likewise is the hybrid patrol vessels which have been commissioned to improve sustainability.

2.2.7. Port of Antwerp

Port of Antwerp is an independent municipally-owned agency located in Belgium. The port is one of the most technologically advanced ports in the world and accessible 24 hours a day, all through the week. Port of Antwerp is also committed to sustainability and particularly achieves this through cooperation with Natuurpunt; an organization that protects flora and fauna habitation.

Port of Antwerp stimulated the installation of technologies that will aid in reducing atmospheric emissions i.e. scrubber systems and selective catalytic reduction systems (SCR), the development of LNG as an alternative fuel and a financial contribution where the ships arriving at the port makes certain contribution to the proper disposal of ship wastes are also noteworthy initiatives that have helped to combat emissions.

At the Port of Antwerp, opening hours of rail facilities were extended which increases the amount of cargo being transported through this channel and in turn reduces the overall generated emission.

In the hope of energy effectiveness, installation of wind power is projected to double renewable energy in subsequent years.

Table 1. Summary of Port Sustainable Practices

Environmental Challenge	Port of Los Angeles and Port of Long Beach	Port of Oakland	Port of Vancouver	Port of Rotterdam	Port of Antwerp
1. Air pollution	Clean Air Action Plan which includes:	Clean Truck Program;	Smart Fleet: initiative that allows tracking of trucks using GPS technology	Shipping index to incentivize green vessels	Technology to reduce air emissions; scrubber systems
	Clean Truck Program (CTP) progressive ban on heaviest polluting trucks	Truck ban in compliance with CARB in addition to a port licensing registry	Single reservation system to improve efficiency	Green Awards program rewards ships for meeting best practices	LNG as alternative fuel for ships
	Encouraging the purchase of LNG trucks through subsidy	Truck financing	Trucking licensing system to meet criteria; idling time, truck age and opacity testing	Infrastructure to make available electrical shore side power	
	Concession and Environmental cargo fee	Extended gate hours and staggered breaks for terminal operators.	Increased gate hour operations	Initiative to capture and store CO2 from CHEs in empty gas fields	
	Green ship incentive index to financially reward ships that meet IMO standards		Container Vessel On-Time Incentive program: discounts for ships that meet scheduled time	Hybrid powered harbor crafts	
	Vessel speed reduction to 12knots within 20 nautical mile from port		Eco Action program rewards ships for meeting best practices		
	Availability of electrical power as alternative maritime power at berth		Infrastructure to make available electrical shore side power		
	Replacement of CHEs to zero emission				
	Mandating harbor crafts to use low-sulphur fuel				

Environmental Challenge	Port of Los Angeles and Port of Long Beach	Port of Oakland	Port of Vancouver	Port of Rotterdam	Port of Antwerp
2. Biodiversity		Wetland restoration and development of ecological reserve	Developed ECHO program to reduce threat to marine lives.		
3. Water quality	Developed Storm Water Pollution Prevention program; port water clean-up, training, inspection,	Adopted guidance from the Municipal Storm Water Program	Institutionalized policies to prevent water pollution	Assesses ecological risks and develops necessary corrective initiatives	
	Identifies pollution sources, gathers information and determine optimal course of action; dredging channels				
4. Energy and Others	Solar, wind and geothermal power serve as alternative sources		An energy plan to replace inefficient energy machineries		Installation of wind power
	Efficient usage of energy consumption; LED bulbs				

2.3. Port Sustainability Indicators

Performance indicators are the fundamentals of any system; biological, chemical, economic, environmental, physical or social (Jakosbsen, 2008). Ports are examples of complex system with a number of variables interplaying at particular period (Bichou and Gray, 2005) and to continuously improve this system's performance with respect to an objective, it is essential to track and benchmark the state of the system at varying point in time (Donnelly et al., 2007).

As mentioned in earlier sections, the advantages of sustainable development to ports cannot be overstated. Although these advantages are known to the port authorities, there is not enough research to validate a standard set of sustainable indicators to be used by ports (Peris-Mora et al., 2005) because most of the port performance research in the past concentrated on productivity and efficiency (Kisi et al., 1999; Thomas and Monie, 2000; Wu and Lin 2008). This situation is even more apparent to the North American ports. Therefore, one of the objectives of this research is to develop sustainability indicators for North American ports which can also be adapted to other ports globally.

Puig et al. (2014) highlighted the top-down and bottom-up approaches as two ways of choosing performance indicators. In the top-down method, indicators are selected from reviewing past literature while the bottom-up method allows us to choose indicators based on relevant stakeholders. In this research, we adopted a combination of both approaches by extensively reviewing literature and port authority websites as necessary and involving port stakeholders' (e.g. Director, Business Intelligence and Innovation, Port of Montreal) inputs to filter the shortlisted indicators. Table 2 shows the list of indicators identified by discussion with academic and ports from literature review.

Peris-Mora et al. (2005) applied fundamental techniques of implementing stage diagrams and system models to identify twenty-one port activities in the port of Valencia. An initial 63 environmental indicators were identified. However, they were reduced to 17 environmental performance indicators having been assessed against a number of objective criteria.

Lirn et al. (2012) studied three of the largest ports in Asia to identify indicators that are most important and suggested recommendations to improve sustainability. They identified 17 green indicators which were classified into five dimensions. Through their developed framework, they were able to prioritize the essential indicators as air pollution management, aesthetic and noise pollution management, solid waste pollution management, liquid pollution management, and marine biology preservation and recommended potential solutions to improve port sustainability. Chen and Pak (2017) also reviewed three other Chinese ports. However, they suggested six dimensions of twenty-one performance indicators. The primary difference between Chen and Pak's (2017) research and that of Lirn et al. (2012) is the addition of the organizational and management dimension

Using both theoretical and practical approaches, Puig et al. (2014) identified 304 indicators and grouped them into 25 sub-categories based on the port performance indicators: selection and measurement (PPRISM) framework. They further categorized the identified indicators into three broad segments; management, operational and environment condition (ISO 14031). Implementing the practical approach, they discussed with relevant port stakeholders representing the EU to shortlist a set of qualitative and quantitative indicators; 9 environmental management indicators and three operational indicators. A major takeaway is the removal of environmental condition because every port's operation is unique to itself.

Bergmans et al. (2014) qualitatively reviewed Antwerp's sustainability reporting initiative from a co-production perspective. They found that beyond the environmental issues, there was a community participation challenge which they addressed by grouping the indicators into two dimensions; environmental nuisance, stakeholder engagement, and public participation. Within the environmental nuisance dimension, indicators such as preparedness to receive, register and deal with complaints, light, noise, odor, littering and air pollution were identified. Regarding the second dimension, public access to information and transparency of procedures, strengthening of place attachment, investments in social capital, and creation and integration of opportunities for social reflection were indicated. Due to the qualitative nature and involved dialogue, a differentiating factor of these indicators from other literature is the sense community that is developed while going through the process.

Walker (2016) reviewed the Green Marine Environmental Program (GMEP) and identified fourteen indicators. Eleven of the performance indicators are established and in use by the Green Marine (GM) registered port terminals and ships while the remaining three are being developed for future references. GM measures each indicator across five levels, namely, monitoring of regulations, systematic use of a defined number of best practices, integration of best practices into an adopted management plan and quantifiable understanding of environmental impacts, introduction of new technologies, and excellence and leadership.

Perera and Abeysekara (2016) measured environmental sustainability with balanced scorecards and Analytical Hierarchical Process (AHP) to establish

Table 2: Port sustainability Indicators and sub-indicators by academicians and ports

Environmental Indicators	Orientation	Sub-Indicators \ Journal Title/ Port Authorities	Black (1996)	Peris-Mora et al. (2005)	Lim et al (2012)	Chen & Pak (2017)	Puig et al (2014)	Bergmans et al (2014)	Walker (2016)	ESPO (2017)	Perera & Abeysekara (2016)	POLA and POLB	Port of Oakland	Port of Vancouver	Port of Rotterdam	Port of Antwerp
Air pollution	*Output*	1. Air pollution avoidance			✓											
	Output	1.1. Air quality (atmospheric contaminant emissions: CO, NOx, SO, O, PM10)		✓				✓		✓	✓	✓	✓	✓	✓	✓
	Output	1.2. Gas emissions with Greenhouse effect (CO2, CH4, N2O)		✓			✓		✓	✓	✓	✓	✓	✓	✓	✓
	Input	2. Using substitute and energy saving devices			✓	✓						✓			✓	✓
	Input	2.1. Using electrically powered equipment to replace the diesel ones, cold ironing (on shore-side power supply)			✓	✓			✓	✓		✓	✓	✓	✓	✓
	Input	3. Reducing vessel speed after landfall to reduce fuel consumption and pollution			✓							✓		✓	✓	✓
Biodiversity	*Output*	1. Ecological preservation			✓											
	Output	1.1. Marine ecosystems			✓	✓			✓	✓						
	Output	1.2. Terrestrial habitats			✓				✓	✓						
	Input	2. Port entrance sediment and coastal erosion control			✓	✓										
	Input	3. Creation of sludge from dredging		✓												
Environmental management	*Input*	1. Existence of an environmental policy					✓			✓						
	Input	1.1. Regulations on the emissions of toxic gas	✓		✓	✓								✓	✓	✓
	Input	1.2. Regulation on noise and vibration from unloading and discharging equipment	✓	✓	✓	✓		✓		✓	✓					

Environmental Indicators	Orientation	Sub-Indicators (rows) / Journal Title/ Port Authorities (columns)	Black (1996)	Peris-Mora et al. (2005)	Lirn et al (2012)	Chen & Pak (2017)	Puig et al (2014)	Bergmans et al (2014)	Walker (2016)	ESPO (2017)	Perera & Abeysekara (2016)	POLA and POLB	Port of Oakland	Port of Vancouver	Port of Rotterdam	Port of Antwerp
	Input	2. Existence of an Environmental Management System					✓			✓						
	Input	3. Environmental policy makes reference to ESPO's guidelines documents					✓			✓					✓	✓
	Input	4. Existence of an inventory of relevant environmental legislation					✓			✓						
	Input	5. Existence of an inventory of Significant Environmental Aspects (SEA)					✓			✓						
	Input	6. Definition of objectives and targets for an environmental improvement					✓			✓		✓	✓	✓	✓	✓
	Input	7. Existence of an environmental training program for port employees				✓	✓			✓	✓					
	Input	8. Existence of an environmental monitoring program					✓			✓		✓	✓	✓	✓	✓
	Input	9. Environmental responsibilities of key personnel are documented (Green Port Development) and exclusive budget				✓				✓						
	Input	10. Publication of a publicly available environmental report				✓	✓	✓		✓		✓	✓	✓	✓	✓
		11. Social and Community Impact							✓							
	Output	11.1. Relationship with local community						✓		✓						✓
	Input	11.2. Preparedness to receive, register and deal with complaints						✓							✓	
	Output	11.3. Social image of the port		✓												
	Output	11.4. Strengthening of place attachment						✓								✓

Environmental Indicators	Orientation	Sub-Indicators \ Journal Title/ Port Authorities	Black (1996)	Peris-Mora et al. (2005)	Lirn et al (2012)	Chen & Pak (2017)	Puig et al (2014)	Bergmans et al (2014)	Walker (2016)	ESPO (2017)	Perera & Abeysekara (2016)	POLA and POLB	Port of Oakland	Port of Vancouver	Port of Rotterdam	Port of Antwerp
	Input	11.5. Investments in social capital for participation						✓								✓
Noise pollution	*Output*	1. Total intensity of noise emitted by vehicles and handling equipments	✓	✓	✓	✓		✓		✓	✓					
	Output	2. Aesthetic interference/visual impact/improving city scenery			✓								✓			
	Output	3. Light						✓								
	Output	4. Odor						✓								
Resource consumption	*Input*	1. Dry bulk handling and storage							✓							
	Input	2. Port development (land related)								✓						
	Input	3. Water consumption		✓			✓			✓	✓					
	Input	4. Efficient energy consumption		✓												
	Input	4.1. Using renewable energy resources such as solar heat and wind power				✓					✓					✓
	Input	4.2. Applying new energy saving working processes		✓		✓				✓	✓					
	Input	4.3. Quay crane and yard crane diesel consumption									✓					
	Input	4.4. Average fuel consumption of vehicle fleet/equipment									✓					
	Input	5. Efficient time consumption														
	Input	5.1. Hours of preventive maintenance									✓					
	Input	5.2. Time spent idling									✓					
Solid waste pollution	*Input*	1. Avoiding the dust pollutants and littering during port maintenance and cargo handling	✓		✓	✓		✓		✓		✓				
	Output	2. Soil quality		✓						✓						

Environmental Indicators	Orientation	Sub-Indicators \ Journal Title/ Port Authorities	Black (1996)	Peris-Mora et al. (2005)	Lim et al (2012)	Chen & Pak (2017)	Puig et al (2014)	Bergmans et al (2014)	Walker (2016)	ESPO (2017)	Perera & Abeysekara (2016)	POLA and POLB	Port of Oakland	Port of Vancouver	Port of Rotterdam	Port of Antwerp
	Output	3. Hazardous cargo waste				✓				✓						
	Output	4. Waste dumping management			✓	✓	✓		✓					✓		
	Output	5. Using recyclable resources			✓						✓	✓				
	Output	6. Urban and dangerous waste creation		✓												
Water pollution	*Input*	1. Alteration of sea floor		✓												
	Input	2. Dredging Operations								✓						
	Input	3. Fuel spilling quantity, contingency plan, control and prevention		✓	✓	✓			✓	✓	✓				✓	
	Input	4. Sewage treatment	✓		✓											
	Input	5. Ballast water pollutant prevention	✓		✓	✓						✓	✓	✓		

Economic Indicators	Orientation	Sub-Indicators \ Journal Title/ Port Authorities	UNCTAD (1976)	Leonard (1990)	Roll and Hayuth (1993)	Trujillo and Nombela (1999)	Thomas and Monie (2000)	Bichou and Gray (2004)	Cullinane and Wang (2007)	Lazano et al (2010)	Sharma and Yu (2010)	Li et al (2013)	Wanke (2013)	Guimaraes et al. (2014)	Bray et (2014)
Financial	*Output*	1. Revenue													
	Output	1.1. Berth occupancy revenue per ton of cargo	✓												
	Output	1.2. Cargo handling revenue per ton of cargo	✓												
	Output	1.3. Total income				✓									

			UNCTAD (1976)	Bendall and Stent (1987)	Hassa et al (1993)	Roll and Hayuth (1993)	Kisi et al (1999)	Trujillo and Nombela (1999)	Thomas and Monie (2000)	Fourgeaud (2000)	Cullinane and Wang (2007	Lazano et al (2010)	Sharma and Yu (2010)	Li et al (2013)	Wanke (2013)	Bray et al. (2014)
	Input	2. Expenditure														
	Input	2.1. Capital equipment expenditure per ton of cargo	✓		✓											
	Input	2.2. Labor expenditure	✓													
	Input	2.3. Total expenditure (gross or net registered tonnes)				✓										
	Output	3. Profit														
	Output	3.1. Contribution per ton of cargo	✓						✓							
	Output	3.2. Total contribution	✓													
	Output	3.3. Operating surplus (value add)		✓		✓										
Production Measures (throughput)	*Output*	1. Ship throughput						✓								
	Output	2. Quay transfer throughput						✓								
	Output	3. Container throughput			✓			✓		✓	✓	✓	✓	✓	✓	✓
	Output	4. Receipt/delivery throughput						✓								

Technical Indicators	Orientation	Journal Title/ Port Authorities Sub-Indicators	UNCTAD (1976)	Bendall and Stent (1987)	Hassa et al (1993)	Roll and Hayuth (1993)	Kisi et al (1999)	Trujillo and Nombela (1999)	Thomas and Monie (2000)	Fourgeaud (2000)	Cullinane and Wang (2007	Lazano et al (2010)	Sharma and Yu (2010)	Li et al (2013)	Wanke (2013)	Bray et al. (2014)
Operational	*Input*	1. Timing														
	Input	1.1 Arrival Date	✓													
	Input	1.2. Waiting time	✓					✓								✓
	Input	1.3. Service time	✓													
	Input	2. Ship														
	Input	2.1. Number of ships			✓		✓									

Technical Indicators	Orientation	Journal Title/ Port Authorities / Sub-Indicators	UNCTAD (1976)	Bendall and Stent (1987)	Hassa et al (1993)	Roll and Hayuth (1993)	Kisi et al (1999)	Trujillo and Nombela (1999)	Thomas and Monie (2000)	Fourgeaud (2000)	Cullinane and Wang (2007	Lazano et al (2010)	Sharma and Yu (2010)	Li et al (2013)	Wanke (2013)	Bray et al. (2014)
	Input	2.2. Average turnaround time in port	✓		✓		✓	✓							✓	
	Input	2.3. Tonnage per ship	✓													
	Input	2.4. Fraction of time berthed ships worked (working time at berth)	✓					✓								
	Input	2.5. Tons per ship-hour in port	✓													
	Input	2.6. Tons per ship hour at berth	✓													
	Input	3. Labor														
	Input	3.1. Number of gangs employed per ship per shift	✓					✓								
	Input	3.2. Tons per gang hours	✓													
	Input	3.3. Fraction of time gangs idle	✓													
	Input	3.4. Number of labor units				✓	✓							✓		✓
	Input	3.5. Total working time					✓									
	Input	3.6. Cargo dwell time			✓		✓	✓								
		4. Cargo														
	Input	4.1. Tonnage of handled cargo			✓		✓									
	Input	4.2. Average weight of containers								✓						
		5. Berth														
	Input	5.1. Number of berth and berth occupancy rate (quay)					✓	✓			✓	✓			✓	✓
	Input	5.2. Length of berth (quay)					✓					✓	✓			

Technical Indicators	Orientation	Journal Title/ Port Authorities Sub-Indicators	UNCTAD (1976)	Bendall and Stent (1987)	Hassa et al (1993)	Roll and Hayuth (1993)	Kisi et al (1999)	Trujillo and Nombela (1999)	Thomas and Monie (2000)	Fourgeaud (2000)	Cullinane and Wang (2007	Lazano et al (2010)	Sharma and Yu (2010)	Li et al (2013)	Wanke (2013)	Bray et al. (2014)
	Input	5.3. Unproductive moves								✓						
	Input	5.4. Automation level of gantry canes								✓						
	Input	6. Terminal area									✓	✓	✓			✓
	Input	7. Commercial constraints (leading to uneven distribution calls)								✓						
Productivity Measures	*Output*	1. Ship productivity							✓							
	Output	2. Crane productivity							✓							✓
	Output	3. Quay productivity		✓					✓							
	Output	4. Terminal area productivity							✓							
	Output	5. Equipment productivity							✓							
	Output	6. Labor productivity							✓							
	Output	7. Cost effectiveness							✓							
Utilization Measures	*Input*	1. Quay utilization							✓							
	Input	2. Storage utilization							✓							
	Input	3. Gate utilization							✓							

environmental performance indicators for three container terminals in Sri Lanka. They identified eight environmental dimensions, namely, materials efficiency, waste management, water consumption, energy use, equipment usage, emissions, water quality, and environmental management.

In 2017, European Sea Port Organization (ESPO) reported the 23 performance indicators tracked across 91 ports in 21 countries. These indicators were segmented into four categories with the top 4 environmental challenges for the year as air quality, energy consumption, noise pollution and water quality.

2.4. Port Sustainability Measurement

Benchmarking is the systematic comparison of the performance of one firm against others (Pau Morales-Fusco et al., 2016). It is a tool that provides an avenue for improvements through assessment of operating performance. The performance assessment of a firm can be regarded in three main aspects; efficiency, productivity, and quality. These, with other factors influence the benchmarking technique to measure the relative efficiency of a firm. Broadly categorized, the approaches can be broken down into three segments; linear programming methods, economic or statistical techniques, and process approaches (Khetrapal et al., 2014).

Within the programming method, Data Envelopment Analysis (DEA) and Free Disposal Hull (FDH) approach are the most used. DEA is a non-parametric approach that uses linear programming to determine the efficient practice frontier of a sample (Farell, 1957). When compared to other techniques, it has an advantage that it does not need to employ an assumption for the functional form of the frontier other than the minimum piecewise and linear condition. Another advantage is that it considers only the most efficient firms in shaping the frontier. Since it is a relatively simple technique, it is the most widely used benchmarking technique in the port industry. However, two critical disadvantages of DEA are the allocation of deviations from the frontier to inefficiency. This assumption can be falsified since the deviation can be caused by other variables like omitted cost drivers and measurement errors. Second, sensitivity to outliers. On a slightly different note, (Deprins et al., 1983) proposed the elimination of the convexity assumption in the DEA and hence the birth of FDH term. FDH efficiencies are higher than DEAs with more self-efficient firms (Tulkens, 1993) and a significant drawback to the approach is that random errors are ignored.

Deterministic statistical approach (DSA) and stochastic frontier approach (SFA) are the core deviations of the statistical techniques. Corrected ordinary least squares (COLS) which are a standard regression technique estimates the efficient frontier from residual. (Khetrapal et al., 2014). The advantages of COLS method are that it is computationally easy, can estimate the impact of factors that affect a firm's efficiency, not controlled by management excluding outputs. For example, in the water sector, climate and terrain will be considered outside the management's control. Critical drawbacks of this approach are it is impossible to measure statistical noise (Greene, 1993), sensitivity to outliers since the frontier is a function of the correction of the average line. Stochastic frontier analysis (SFA) is a parametric and stochastic approach that uses maximum likelihood estimation techniques to approximate the frontier efficiency. The advantages of SFA is that it recognizes the presence of errors and tries to distinguish them from the inefficiency measures. Also, there is a possibility to model the effects of exogenous variables. However, a significant drawback is that it is subjected to theoretical objections since it uses the half-normal and exponential distribution.

Beyond the advantages that DEA has over the other techniques, there has been an increase in the use of DEA for measuring port efficiency which is mainly associated to its methodological and computational benefits suited for complications in the port environment (Panayides et al., 2009). Although stochastic frontier is a strong competitor when deciding approaches for measuring port efficiency, it is difficult to agree on the most valid technique in this context (Gonzalez and Trujillo, 2007). Hence, we decided to continue with the DEA for its advantages and diversity identified in various studies.

2.4.1. Efficiency Measures

The productivity of a decision making unit is defined as the ratio of its output to its input (Lowell, 1993). However, when the discussion transcends to more than one output or input, then a different term is considered – efficiency. Although some authors use the terms productivity and efficiency interchangeably, the efficiency of a production unit can be described in terms of a comparison between observed and optimal values of its output and input (Lowell, 1993). Koopmans (1951) defined an input-output vector as technically efficient if, and only if, increasing any output or decreasing any input is possible only by decreasing some other output or increasing some other input. Debreu (1951) established the initial measure of productive efficiency for analyzing his concept of coefficient of resource utilization.

Farell (1957) built on the work of Koopmans (1951) and Debreu (1951) to define a measure of production efficiency that accounts for multiple inputs. He defined production efficiency as the product of technical and allocative efficiency. Technical efficiency measures a firm's success in producing maximum output from a given set of inputs while allocative efficiency measures its success in choosing an optimal set of inputs with a given set of input prices. Another efficiency that is worth mentioning is structural or scale efficiency; at an industry level, measures the extent to which an industry keeps up with the performance of its own best firms. In other words, comparing an industry's performance with the efficient production function derived from its constituent firms. The efficiency analysis in our research is focused on technical and scale efficiencies, whose elaborate definitions will be given in chapter 3.

2.4.2 DEA Port Benchmarking

Optimization has been used by many researchers for port benchmarking. As reviewed in the previous section, the Farrell efficiency concept can be explained as the maximum proportional contraction of all inputs that allows the production of the same amount of output. The major drawback of the Farrell efficiency is the attribution of weights to the inputs and outputs. To overcome this drawback, Charnes, Cooper, and Rhodes (CCR) (1978) developed the first and fundamental DEA model which is based on mathematical programming. They created the DEA method with constant returns to scale (CRS) or the CCR. This method is built on the notion of efficiency as defined in classical engineering ratio. The CCR allows the measurement of the relative efficiency of decision-making units (DMUs) without attributing any predetermined weights or conducting any time series analyses. This CCR was improved upon by Banker, Charnes, and Cooper (BCC) (1984) to include variable returns to scale (VRS) and is also known as BCC. Although the DEA method has been improved upon in multiple ways by incorporating dummy or categorical variables, Malmquist indices, etc., it is still the most widely used DEA model.

DEA has been used widely for the comparison of analogous units such as container ports. Table 3 provides a summary of DEA used in literature to evaluate the relative efficiencies of container ports specifically. The sample size in the literature spans between 10 and 100 DMUs. The most commonly applied DEA methods are the traditional ones i.e CCR and BCC by Charnes, Cooper, Rhodes, and Banker.

DEA was first applied by Roll and Hayuth (1993). Using panel data, Bichou (2013) shows that several container terminals make use of a VRS technology. Cullinane and Wang (2007) used the traditional CRS and VRS DEA model and their discovery indicates a correlation between large ports and decreasing returns to scale, and between small ports and increasing returns to scale. Tongzon (2001) identified the failure to optimally utilize labor as one of the predominant reference of inefficiency for 92% of ports analyzed. The findings of CRS for Middle East container terminals suggests 16 out of the 19 sampled terminals are inefficient (Almawsheki & Shah, 2014). Wanke (2013) used a two-stage network DEA model to compute shipment efficiency levels, highlighting 25.9% of the ports achieved 100% efficiency in stage one. Finally, using a three-stage DEA model, Li, Luan and Pian (2013) assess the efficiency of Chinese coastal container terminals. Due to scale inefficiency, the general terminal efficiency is low. However, the difference in terminal efficiency across the port groups is quite large which begs for more analysis. Hung et al. (2010) report that technical inefficiencies, as opposed to scale inefficiencies, are the primary cause of the comprehensive technical inefficiency of container ports. This empirical result implies that port managers need to put more emphasis on improving their management practices to meet the market requirements of container ports, and then container ports can be subject to improvements in their scale efficiencies. The summary of the studies' results supports the assumption that technical efficiency is dependent on the ownership regime of inputs deployed in the production process. With respect to ports, the most often used inputs are usually the terminal area, the quay length, the number of container berths, the number of quay cranes, and the number of employees. The most applicable index to evaluate the ports' economic standard is the annual container throughput in TEUs (Wayne Kelly, 2006), as the bottom line of container terminals is to process as many containers as possible. This implies that higher levels of container throughput will correspond to higher efficiency level assuming the same amount of inputs.

However, this procedure may lead to inaccurate results considering the environmental impact of port and related transport activities. The second set of literature review identifies some of the approaches used by researchers to compute efficiency scores while taking into consideration the environmental impact of ports operations. The general ideology is to consider two outputs; container throughput along with CO_2 emitted by the decision-making units. CO_2 emitted, in this case, can either be directly or indirectly. The former represents emission from its operations whereas the latter is associated with the other operations, i.e., rail, ship, truck, etc. These DEA methods are extensions of the traditional methods reviewed earlier, and by including undesirable outputs, they are used to measure eco-efficiency, hence, the name eco-DEA or environmental DEA models (Haralambides, Gujar, 2012).

There are five ways to conduct an eco-efficiency benchmarking analysis:

1. *Ignoring undesirable outputs:* In (Nakashima et al., 2006; Lu and Lo, 2007a,b), the traditional DEA technique is used, and undesirable outputs are not considered.
2. *Treating undesirable quantities as inputs:* Here, the undesirable output is modeled as an input (Dyckhoff and Allen, 2001). This technique may not reflect the reality of container port industry since there are no penalties that may directly hinder operational efficiency. A container port increase in container throughput efficiency hypothetically links to an increase in the amount of CO_2 gas emitted.
3. *Non-linear monotonic decreasing transformation approach:* proposed by Galony and Roll (1989), this technique transforms undesirable output into a desirable output using a monotonically decreasing function f of the form: $f(u_i^k) = 1/u_i^k$, where u_i^k is the i^{th} element

of the vector *u* of undesirable outputs of DMU *k.* The idea is that the performance will be inversely related to the undesirable output. In the comparison of the macroeconomic performance of 19 Organization for Economic Corporation and Development (OECD) countries, the reciprocals of undesirable outputs were treated as normal outputs (Lovell et al., 1995)

4. *Linear monotonic decreasing transformation:* proposed by Seiford and Zhu (2002), the technique transforms undesirable output given by the function $f(u_i^k) = -u_i^k + B_i$, where B_i is a sufficiently large positive scalar. Lu and Lo(2007b) used this approach to assess the performance of regions in China, based on economic and environmental factors. However, the model has been criticized for its invariance to data transformation.
5. *Treating undesirable factors in non-linear DEA models:* based on the Fare et al. (2004) non-linear approach, it establishes its basis on the weak disposability of undesirable output theory suggested by Zhou et al. (2007). Yang and Pollitt (2010) describe weak disposability as either being too costly to reduce undesirable output since there will be an increase in inputs or decrease in desirable outputs. Hence, the undesirable output is modeled as a normal output and adjusted by optimizing the distance measurement of the undesirable output (Liu, 1995). This approach was used to develop a performance index to assess the environmental performance of 28 OECD countries (Yoruk and Zaim, 2008). Expressed as

$$C = (B-A) \qquad (2.1)$$

$$A^* = A\,(1-C) \qquad (2.2)$$

Where, A is defined as efficiency score obtained by the conventional DEA model without considering the undesirable output, B is the efficiency score obtained by the conventional DEA model with the incorporation of undesirable outptut, and C is the environmental impact brought by the undesirable output.

Table 3 Summary of DEA uses in literature

Authors	Model	Sample and region	Inputs	Outputs
Roll and Hayuth (1993)	CRS, Cross sectional	20 container ports	Size of labor force, Annual investment per port, uniformity of facilities and cargo	Container throughput, Service level, User satisfaction, Ship calls
Sharma and Yu (2010)	DT based context-dependent DEA	70 container terminals	Quay cranes; Transfer cranes; Straddle carriers; Reach stackers; Quay length, Terminal area	Container throughput
Bray et al. (2014)	Fuzzy DEA	16 container ports	Number of cranes; Container berths; Number of tugs; Terminal area; Delay time; Number of port authority employees	Container throughput; Ship rate, Ship calls, Crane, Productivity
Cullinane and Wang (2007)	CRS, VRS	57 container ports	Terminal Area; Quay cranes; Yard cranes Straddle Carriers	Container throughput
Bichou (2013)	CRS, VRS, Panel data	420 container terminals	Terminal area; Max draft; Quay length Quay crane Index; Yard-stacking index Gates	Container throughput
Wanke (2013)	Network-DEA centralized efficiency	27 Brazilian ports	Number of berths; Warehousing area Yard area; Container frequency (shipments)	Container throughput
Lozano, Villa and Canca (2010)	Centralised DEA using a non-radial Russell measure of technical efficiency.	50 Spanish container ports	Land and stacking area; Total quay length Total number of cranes; Number of tugs	Total port traffic Container Throughput Ship calls
Guimaraes et al. (2014)	CRS, VRS	15 Brazilian container terminals	Total Energy; Non-renewable energy Sewage emission; Office supplies consumption; Total emissions and Water consumption per worker	Container Throughput
Cullinane, Wang, Song, & Ji (2006)	CRS, VRS, Cross sectional	30 container ports, Worldwide	Terminal length; Terminal area; Quay cranes Yard gantry cranes; Straddle carriers	Container throughput
Almawsheki and Shah (2015)	CRS	19 container terminals in the Middle East	Terminal Area; Quay length; Quay cranes; Yard equipment; Maximum Draft	Container throughput
Garmendia and Schwartz (2015)	CRS, VRS	63 container ports in Latin America and the Caribbean	Quay length; Terminal area; Mobile cranes with more than 14 t. capacity; STS gantry cranes	Container throughput
Gonzales and Trujillo (2008)	Parametric and DEA	10 Spanish ports	Length of berths; Port area; Number of employees	Containers Liquid bulk Other cargo Passengers
Hai-bo and He-zhong (2009)	SFA	13 port companies in China	Net permanent asset; Total employees	Main business revenue

Authors	Model	Sample and region	Inputs	Outputs
Hung et al. (2010)	CRS, VRS, DEA with bootstrap method	31 container ports in Asia-Pacific	Terminal area; STS container gantry cranes (No); Berths (No); Total quay length	Container throughput
Jiang and Li (2009)	CRS, VRS	12 container ports in Asia	Import/Export by customs; GDP by regions Berth Length; Crane number	Container throughput
Li et al. (2013)	DEA, SFA	42 Coastal ports on China	Terminal length Handling equipment (bridge, mobile and beam cranes) Number of employees	Container throughput
Lim, Bae and Lee (2011)	Additive non-oriented DEA RAM	26 Asian container terminals	Quay length; Total area; Gantry Cranes	Container Throughput
Sanchez and Millan (2012)	Malmquist index	46 ports in Spain	Number of employees; Intermediate consumption; Capital	Liquid bulk Solid bulk Containerized general cargo Non-containerized general cargo
Tongzon (2001)	CRS; Additive DEA.	4 Australian and 12 other international container ports	Number of cranes, Number of container berths, Number of tugs, Terminal Area, Delay time Labor (units), Ship rate	Container throughput Number of shipcalls

Source: Adapted from (Kutin et al., 2017)

2.5. Bibliometric Analysis

There are limited reviews on port sustainability performance benchmarking. In this section, we conduct bibliometric analysis to identify and review the literature progression of sustainability performance benchmarking which will also help us identify research gaps. Bibliometric analysis is "the use of statistical methods to analyze the body of literature" (Yong, 1983). The key components we address are:

1. Provide statistics of the most important journals, authors, and organizations that have contributed to this domain.
2. Identify research areas that provide the field with the knowledge base.

Sub-section 2.5.1 presents the bibliometric analysis methodology. Sub-section 2.5.2 presents the analysis results.

2.5.1 Research Methodology

Rowley and Slack (2004); Saunders et al. (2009) suggested a structured methodology to review the literature of a subject domain. We adopted their structured approach and used a two-step methodology. The first step is to define appropriate search keywords to refine the search results and the second step is the actual analysis of the refined data.

2.5.1.1 Define Search Keywords and Refine Search Results

This process was an iterative one. In addition to this, heuristics were used in defining the search keywords for the data collection phase. The heuristics process involved the following:

i. The initial definition of search terms

ii. Validating the resulting search articles to ensure that it covers major journals

iii. Updating the search terms and deleting irrelevant articles

Scopus database was used for the study, and the 'title, abstract and keywords' search option was employed to download the resulting articles based on the identified keywords in Table 4. The primary reason for using this database is because it is the most extensive abstract and citation database of peer-reviewed literature: scientific journals, books and conference proceedings and presents comprehensive storage of global research across various verticals of education (Scopus, 2018). However, the database does not have information before 1996 which can be a limiting factor depending on the type of information required.

Table 4: Defined keywords and resulting number of articles before and after deleting irrelevant subject domain

Search keywords	**Before**	**After**
Green AND port AND evaluation OR sustainability AND evaluation	103	18
Port AND environmental OR green AND Benchmark OR DEA OR SFA	54	15
Port AND sustainability AND environment AND benchmarking AND performance AND evaluation	39	11
Total	196	44

196 articles were the results of the initial set of identified keywords. However, after refining the articles by going through them individually and excluding the irrelevant one to port sustainability performance benchmarking, the number of articles were reduced to 44. The refining process was done by downloading the data from Scopus database to Excel for necessary data wrangling and further analysis.

2.5.1.2 Data Analysis

The data analysis section involves two parts; bibliometric analysis and network analysis. Excel 2016 and Gephi 0.9.2 were used as the tools in conducting both parts of the analysis. The search results from Scopus database were exported in .csv format and cleaned for detailed network analysis.

2.5.2. Statistics

The bibliometric analysis comprises of the following data variables; authors, title, journal, publication year, keywords, abstract, affiliations, and references. Pivot tables in Excel were the major tool required to pull required statistics.

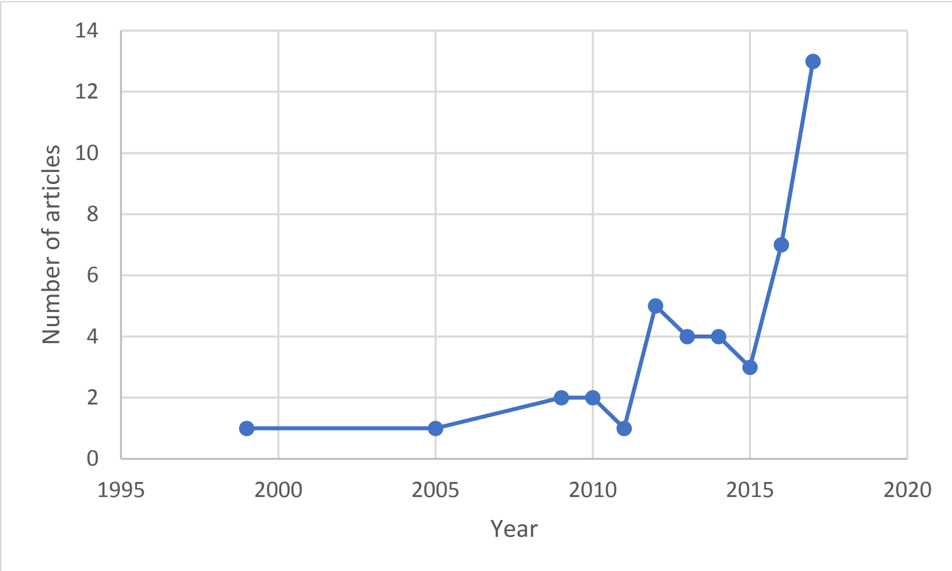
2.5.2.1. Journal statistics

The analysis shows that 34 journals have contributed to the publication of the 44 articles being reviewed and the five most popular journals of the set have 15 publications, which constitutes 34% of the total articles as seen in Table 5. Fig 2 shows the evolving trend of this subject domain over the last 18 years. There has been a general increase in the publication of articles over the years which substantiates the attention sustainability has received in recent times.

Table 5: The most popular host journals and quantity of articles contributed

Journal	**No. of articles**
Advanced Materials Research	4
Marine Pollution Bulletin	3
Maritime Policy and Management	3
Transportation Research Part D: Transport and Environment	3
International Journal of Shipping and Transport Logistics	2
Total	15

Figure 1: Publication trend in the area of port sustainability benchmarking



2.5.2.2. *Author statistics*

Analyzing the frequency of authors who have contributed to the domain, Table 6 shows the six authors who have contributed to more than one article. These authors represent 5% of the 117 authors while the remaining 111 authors have single articles to their names. Table 7 shows the top paired authors and all four authors on this list are part of the 5% who have contributed to more than an article.

Table 6: The most prolific authors

Author	**No. of published articles**
Puig M.	4
Wooldridge C.	4
Darbra R.M.	4
Michail A.	2
Lun Y.H.V.	2
Wu J.	2

Table 7: The most prolific paired authors

Author 1	Author 2	Author 3	No. of joint publications
Puig M.	Wooldridge C.	Darbra R.M.	4
Puig M.	Michail A.		2

2.5.2.3. Affiliation statistics

Counter-intuitively, Asia as a region has more publications in this regard than Europe and North America, with China representing 25% and Spain and Taiwan representing 14% of the total number of articles a seen in Table 8. Table 9 shows the geographic distribution of the top performing organizations and based on our data, more organizations from Asia are affiliated with top contributions to port sustainable performance benchmarking.

Table 8: Geographic location of affiliated organizations

Country	No. of articles
China	11
Spain	6
Taiwan	6
South Korea	4
United Kingdom	4
Hong Kong	2
Netherlands	2
Turkey	2
Australia	1
Belgium	1
Canada	1
Greece	1
Italy	1
Montenegro	1
Sri Lanka	1

Table 9: Top performing organizations

Organization	Country	No. of articles
School of Management, University of Science and Technology of China	China	2
Department of Logistics and Maritime Studies, Hong Kong Polytechnic University	Hong Kong	2
Graduate School of Logistics, Inha University	South Korea	2
Department of Chemical Engineering, Polytechnic University of Catalonia (UPC)	Spain	2
Department of Shipping and Transportation Management, National Taiwan Ocean University	Taiwan	2
Department of Marketing Management, Central Taiwan University of Science and Technology	Taiwan	2

2.5.2.4. Keyword statistics

Tables 10 and 11 shows the most used words in the list of keywords and titles of articles respectively. For the keywords, we have the top 16 words from a pool of 142 unique search keyword list while for the article titles, we have the most frequently used 16 words from a set of 219 words. Refining this data was accomplished with pivot tables and using heuristics to merge relevant words. Some of the most popular words in both cases are as follows; port, environmental, performance, and green.

Table 10: Top 16 word/phrases used in the list of keywords

Keyword phrase	Frequency
Environmental performance	6
Green port	5
Data envelopment analysis	4
Environmental management	4
Port	4
Environmental performance indicators	3
Port management	3

Sustainability	3
AHP	2
DEA	2
Mediterranean Sea	2
Efficiency	2
Seaports	2
Stochastic frontier analysis	2
SFA	2
Sustainable development	2

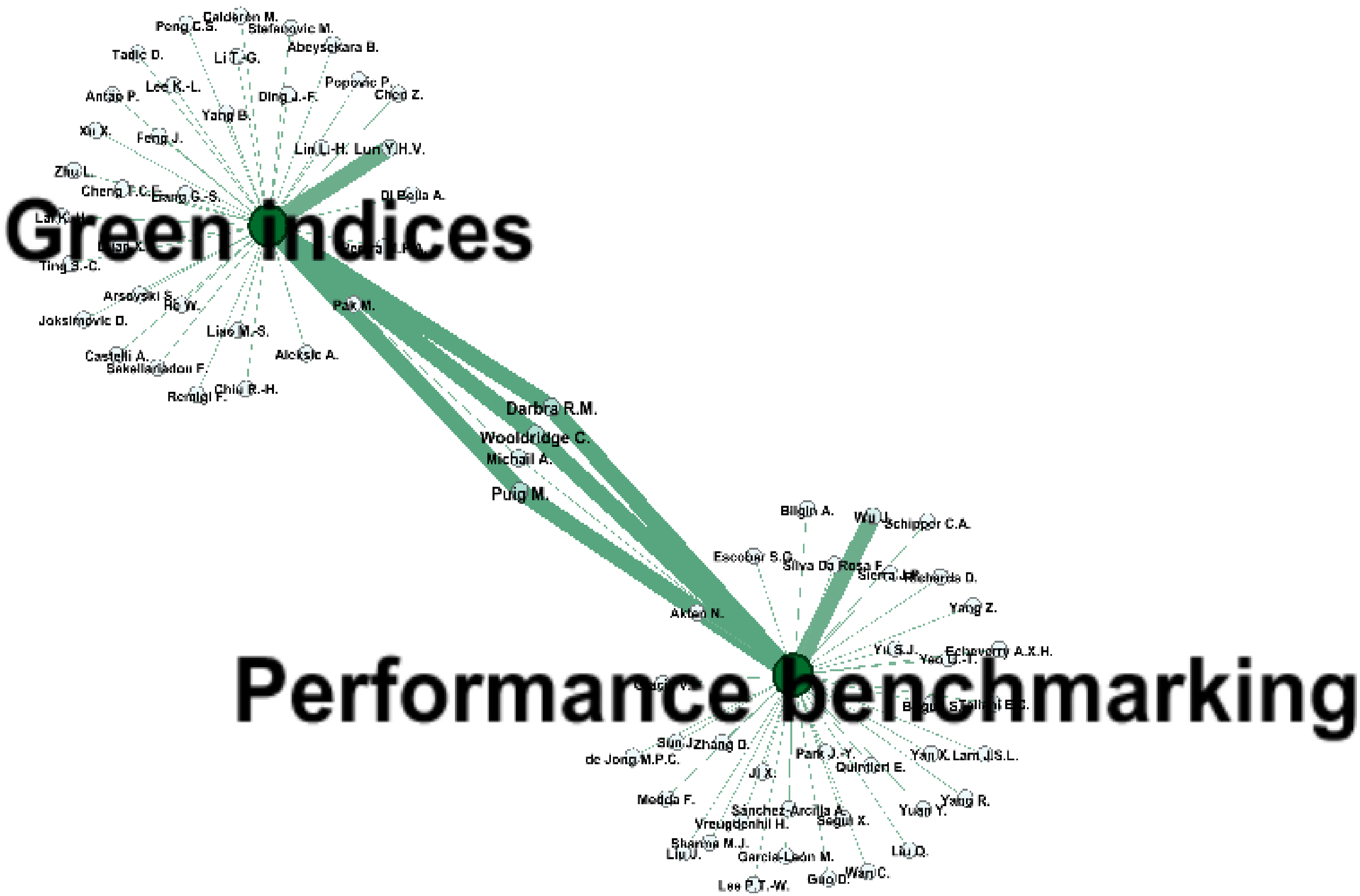
Table 11: Top 16 frequently used words in article titles

Word	**Frequency**
Port	34
Environmental	17
Evaluation	17
Green	13
Performance	12
Container	9
Based	9
Analysis	7
Efficiency	7
Terminal	6
Study	5
Model	4
Approach	4
Case	4
System	4
Mediterranean	4

2.5.3. Network Analysis and Synthesis

In this section, we use bibliometric analysis to understand how the research has evolved. Based on the analyzed data, more attention has been paid since 2012 and a major spike occurred in 2017. The trend implies this is becoming an important area and the number of publications will continue to grow in the coming years. It also shows that environmental performance and data envelopment analysis are some of the top words for benchmarking cases. However, grouping the publications into research clusters, we found out that although there has been some connection between the performance benchmarking cluster and green indices cluster, very few authors have made this contribution (Figure 2). Consequently, having filtered using a degree of 3, Figure 3 indicates these keywords as the most interconnected between the respective articles; port, environmental performance indicators, sustainability, port management, environmental management, environmental performance, key performance indicators, green port, analytical hierarchical process and data envelopment analysis. Finally, it is important to highlight the limitation regarding our analysis. First, our keyword structure is not foolproof and can be improved across other dimensions. Second, the categorization of research cluster is not mutually exclusive or collectively exhaustive, and a further breakdown of these segments can provide finer details. Lastly, the scopus database contains a lot of publications in recent times. However, it does not mean it is absolute with respect to publications. Directional plan for future works can be along the lines of a robust methodology to address the highlighted limitations.

Figure 2: Literature classification – data clustering



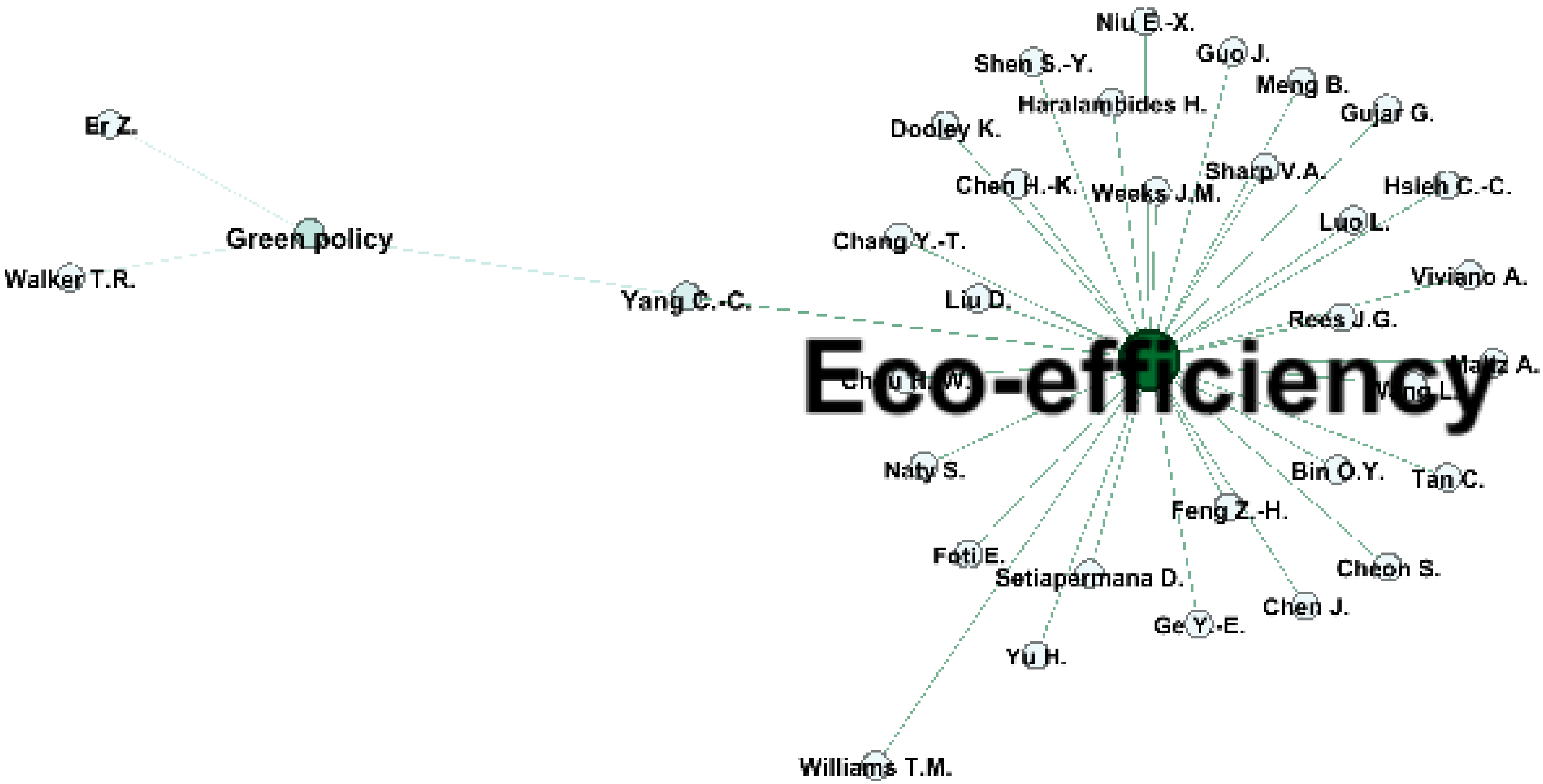
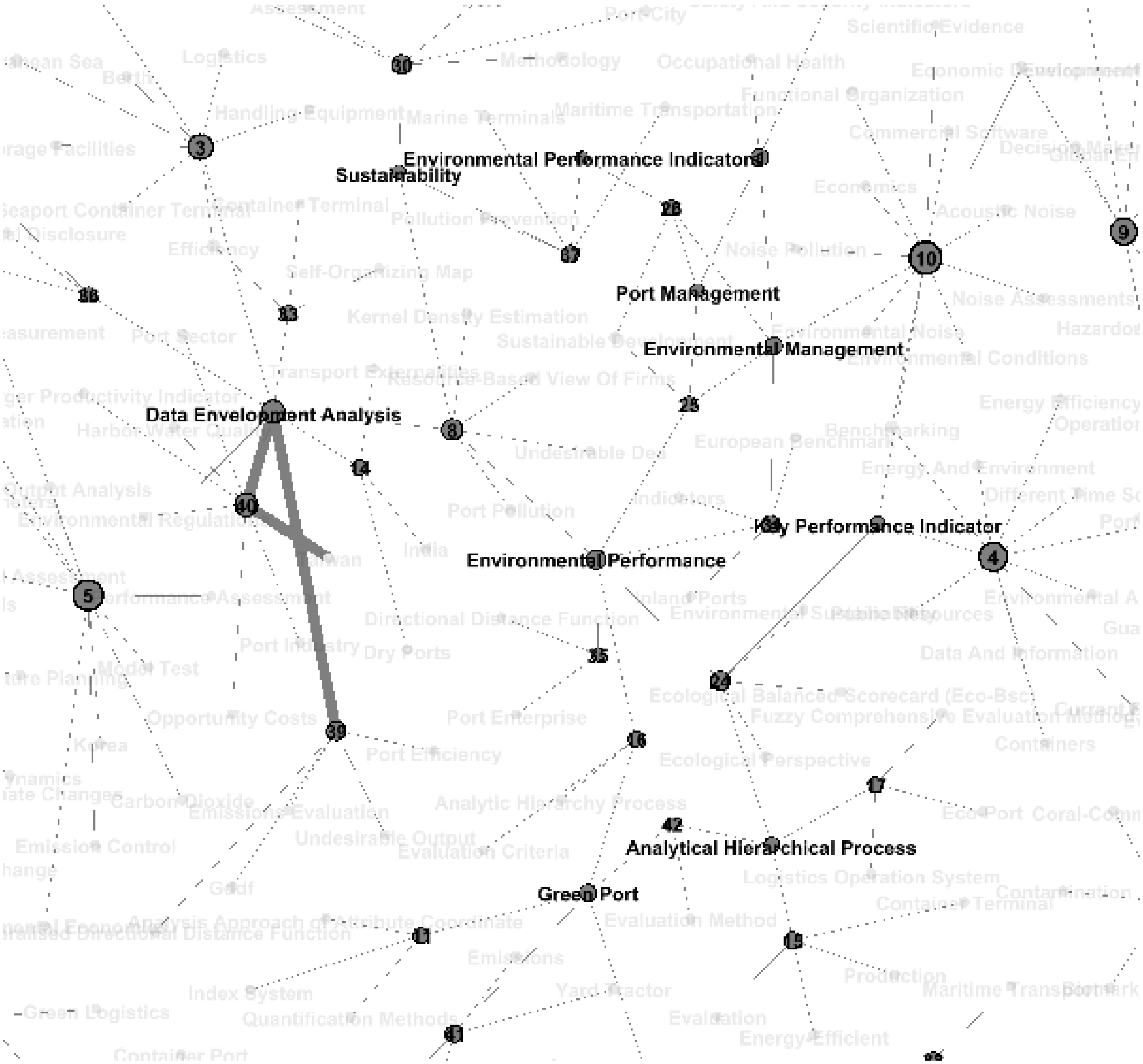

Er Z.
Green policy
Walker T.R.
Yang C.-C.
Niu E.-X.
Shen S.-Y.
Guo J.
Meng B.
Haralambides H.
Dooley K.
Gujar G.
Chen H.-K.
Weeks J.M.
Sharp V.A.
Hsieh C.-C.
Chang Y.-T.
Luo L.
Viviano A.
Liu D.
Rees J.G.
Eco-efficiency
Naty S.
Bin O.Y.
Tan C.
Feng Z.-H.
Foti E.
Cheon S.
Setiapermana D.
Chen J.
Ge Y.-E.
Yu H.
Williams T.M.

Figure 3. Keyword clustering – interconnected


Environmental Performance Indicators
Sustainability
Port Management
Environmental Management
Data Envelopment Analysis
Key Performance Indicator
Environmental Performance
Analytical Hierarchical Process
Green Port

2.6. Research Gap

In this chapter, we reviewed the literature on port sustainability, sustainability initiatives by ports globally, benchmarking approaches to ports both from an operational and ecological efficiency viewpoint, and bibliometric analysis of port sustainability benchmarking. We draw the following insights from these observations regarding research gaps.

First, container ports are complex organizations (Panayides et al., 2009) and it is important to use similar variables for consistency and viable performance benchmarking analysis. However, not enough research validates a standard set of sustainable indicators (Peris-Mora et al., 2005) since most studies focus on productivity and efficiency.

Secondly, variable specifications are crucial to the research but are limited due to the availability or consistency of data. Therefore, an application of uncertainty modeling to tackle imprecision will be interesting to consider. Consequently, using a multiple output-oriented DEA approach that takes into consideration other dimensions of sustainability as undesirable output is better to attempt modeling the reality of port structure.

Lastly, although studies about benchmarking port sustainability performance have been gaining traction in the last decade, a large percentage of these studies focus on environmental aspect and in the Asian and European region. This may be attributed to the increase in trade and technological advancements in these regions. Therefore, expanding our research to address the North American sustainability context will be an important contribution to the region.

Chapter 3

Research Methodology

3.1. Introduction

In the previous chapters, we introduced elements of the data envelopment analysis and reviewed corresponding sustainability literature as applied to container ports. Based on these, our methodology for this study was developed. It comprises of two main steps. Firstly, determine sustainability indicators and secondly evaluate sustainability efficiencies of the container ports using DEA and understand factors that influence these respective efficiencies. The proposed DEA models evaluate both undesirable and desirable outputs for ports. Three categories of models are proposed namely; ignoring undesirable output, treating undesirable output as input, and directional distance function under variable and constant returns to scale. A case study for 13 North American ports is conducted. More details are presented in later sections.

3.2. Overview of Methodological Approaches

Paradigm or philosophy is the underlying belief system that guides the research investigation in answering methodological, epistemological and ontological questions as defined by Krauss (2205) and Collis et al. (2003). Thus, research philosophy is the basis to understand the concept of the research. Creswell (1994) broadly categorized this into two perspectives; positivism and non-positivism. Positivism centers on the belief of the existence of an objective real world and approaches it from a natural science point of view while non-positivism paradigm is based on the subjective and socially constructed worldview. For this research, we align with the positivism perspective more than the other because we use scientific investigation to assess the situation of the port in a deterministic way.

The next level of discussion is the research approach. There are two main approaches namely, deductive and inductive. Deductive approach is a top-down style which is based on logic. A hypothesis is established, and a design strategy to test this hypothesis is developed (Wilson et al., 2010). On the other hand, the inductive approach enables theory generation from observed data. Mapping our definition to this research, it is evident that we tilt towards the inductive style.

Time perspective is an essential element to consider in a study. There are two points of view; cross-sectional and longitudinal. Cross-sectional means merely at the same point of time or without regards to differences in time while longitudinal refers to data collection and comparison over a period. Longitudinal can be further broken down into trend and panel studies. Due to the type of research, we have incorporated the cross-sectional technique. This involves analyzing the ports data in the year 2016 and comparing the variables that are important to the research.

Finally, the approach used in getting information. There are two main approaches; mono-method and multiple method (Saunders et al., 2009). In our case, we applied the multiple method and used various techniques to collect information which is the combination of quantitative and qualitative approaches across a number of sources.

3.3. Identification of Indicators

This step is one of the basics when developing the DEA model, the reason being that the selected variables have a large impact on the analysis precision (Wang et al., 2003). This process involves specifying the two types of variables; inputs and outputs, and we took a two-pronged approach to identifying these variables. First is reviewing the literature to establish validity and conformity of past research as shown in Table 2 and the second is filtering based on heuristics and survey.

3.3.1. Output Variables

The governing thought centers around sustainability, therefore, our output objective is to maximize the positive economic elements and minimize the harmful elements of the environmental and social dimension generated simultaneously.

From an economic standpoint, there are performance indicators that can optimally represent the output objective, e.g., profit, volume of cargo, port container throughput, turnaround time of ships and the number of passengers (UNCTAD, 1976; Chin and Low, 2010; Bichou and Gray, 2004; Chang, 2013). A reasonable argument is that profits of a port are a good indicator that represents the output. However, available annual financial reports only show the cumulative of cargo handling, transportation, logistics, information services, etc. and due to the lack of financial data breakdown, this variable was dismissed from the output variable set. Since the focus is on container ports, it makes sense to exclude the volume of cargo and number of passengers as well. Due to the collinearity between the port container throughput and the number of ship calls, it was decided to choose the container throughput. In addition to these points, a majority of the literature (Table 2) and accredited global port platforms recognize the container throughput as the major economic indicator for container ports.

With respect to the environmental and social dimensions, examples of indicators that satisfy these objectives are solid waste, water pollution, soil pollution, biodiversity, greenhouse gases, other air pollution gases, noise pollution and congestion (Guimaraes et al., 2014; Strezov et al., 2016). Carbon dioxide equivalent CO2eq which consists of carbon dioxide (CO2), methane (NH4) and nitrogen oxide (N2O) was chosen among these dimensions. Although the CO2eq data is not readily available, it was chosen because of its major impact as an undesirable output as mentioned in global sustainability policies. Validated assumptions were taken into consideration to calculate the unavailable data points. Subsequently, we have sewage emission, congestion, and accidents.

Finally, our selection of output variables is narrowed to three sets of variables; one physical economic, two environmental and two social indexes as desirable and undesirable outputs respectively. The primary reason for this restriction is due to the frontier characteristics of the DEA whereby if the number of performance measures is high in comparison with the number of DMUs, then the quality discriminative power of the model is hindered causing more DMUs to be recorded as efficient (Cooper et al., 1985).

$$n \geq \max\{3(m+s), m * s\}$$

Where, *n, m*, and *s* represent the decision-making units, input(s) and output(s) respectively.

3.3.2. Input Variables

Input variables can be categorized into three parts; labor, capital and operational. Terminal area, quay length, berth length, storage capacity, piers and handling equipment (gantry cranes, yard cranes, forklifts), berth accessibility, berth occupancy, operating hours, equipment age and maintenance, total number of equipment, annual cash investment, waiting time and quayside water depth, are some of the examples of indicators that can represent the input variables (Table 2). However, due to the frontier characteristics of DEA as mentioned in section 3.5.1 and collinearity between these variables, it was decided to restrict the indicators to five major ones that best represent the model, namely; number of gantry cranes, terminal area, berth length, investment in technology and environmental policy.

The rationale for these five selected indicators are as follows; within the labor component, it is argued that the number of dockworkers may be a reliable representation, however, due to collinearity between infrastructure and labor, Notteboom et al. (2000) developed a relationship between the number of gantry cranes and the number of dockworker which led to this indicator being selected. In addition to the multicollinearity characteristic mentioned earlier, terminal area and berth length were also selected because they best represent infrastructure, handling capacity and general efficiency which are subsets of the larger operations. For capital input, investment in technology was selected. It is important to note that this is not mutually exclusive to capital as there is a correlation between investment and operational efficiency. Lastly, environmental policy was considered to gauge environmental preparedness. Below is a summary of the chosen input and output variables.

Table 12: Variable specification for port level data

Variable	Indicator	Sub-indicator	Description	Unit
Outputs	Production	Container throughput	Annual cargo processed by a port	TEU
	Air pollution	GHG emissions	CO_2 eq. = CO_2 + CH_4 + N_2O	Metric Tons
	Water and soil pollution	Sewage emission	Fuel and chemical spills, sewage dumping	Liters
	Noise pollution	Congestion	Total intensity congestion from vehicles	
	Accidents	Accidents	Accidents caused as a result of port activates	
Inputs	Operational	Berth length	Facilitates the loading and unloading of ships	Meters
	Operational	Terminal area	Infrastructure that facilities storage capacity & drayage transportation	Acres
	Operational	Number of gantry cranes	Total number of cranes for cargo operation	Units
	Financial	Investment fund	Investment for technology	
	Environmental Management	Existence of environmental policy	Objectives, monitoring program, reporting	

3.4. Development of DEA Model

Data envelopment analysis coined by Charnes, Cooper, and Rhodes (1978) is a non-parametric mathematical programming approach to frontier estimation. As reviewed in chapter 2, many models have been utilized to evaluate performance. We discussed the advantages DEA has over other approaches and the reason why it was chosen for this study.

As stated in the CEPA working papers, the purpose of DEA is to construct a non-parametric envelopment frontier over the data points in such a way that they are plotted on or below the frontier. Let us assume there are *K* inputs and *M* outputs for each of the *N* ports also known as decision-making units (DMUs). For the i^{th} *DMU*, these are represented by the vectors x_i and y_i, where *X* is the *K*N* input matrix, and *Y,* the *M*N* output matrix represent the data of all *N* DMU's.

One of the ways to explain DEA is through the ratio form. For each DMU, we would consider the ratio of all outputs over all inputs, stated mathematically as

$$\frac{u'y_i}{v'x_i} \qquad (3.1)$$

Where:

u is an *M*1* vector of output weights and

v is a *K*1* vector of input weights.

To determine the optimal weights, the linear programming system of equations is given as

$$max_{u,v}\left(\frac{u'y_i}{v'x_i}\right) \qquad (3.2)$$

$$subject\ to\ \frac{u'y_j}{v'x_j} \leq 1,\ j = 1,2,\dots,N, \qquad (3.3)$$

$$u, v \geq 0 \qquad (3.4)$$

This involves finding values for u and v, such that the efficiency measure of the i^{th} DMU is maximized, subject to the constraint that all efficiency measures must be less than or equal to one. A challenge is the infinite number of solutions this ratio formula has. To handle this challenge, an additional constraint $v'x_i = 1$ can be imposed.

Rewriting the initial system of equation in its transformation or multiplier form, we have

$$max_{u,v}\ (\mu' y_i) \quad (3.5)$$

$$subject\ to\ v'x_i = 1 \quad (3.6)$$

$$\mu' y_j - v'x_j \leq 0, j = 1,2, \dots, N \quad (3.7)$$

$$\mu, v \geq 0 \quad (3.8)$$

In the duality form of linear programming, the equivalent system of equation is given as

$$min_{\theta,\lambda}\ \theta, \quad (3.9)$$

$$subject\ to - y_i + Y\lambda \geq 0, \quad (3.10)$$

$$\theta x_i - X\lambda \geq 0 \quad (3.11)$$

$$\lambda \geq 0 \quad (3.12)$$

Where:

θ is a scalar

Y and X are matrices with columns y_i and x_i respectively

λ is a $N * 1$ vector of constraints.

The value of θ will be the efficiency score for the i^{th} DMU. This value will represent a technical efficiency and if equal to 1, then the DMU is technically efficient (Farrell, 1957). It should be noted that N number of DMUs determines the number of times the linear programming problem must be solved with each solution generating a θ value for each DMU.

3.4.1 Slacks

To provide a more accurate technical efficiency, there needs to be a non-zero input or output slack in addition to Farrell's technical efficiency measure (Koopman, 1951). There are some options for calculating slacks. Three most popular methods are; one-stage DEA and calculate the slacks residually, two-stage DEA where the sum of the slacks required to move from an inefficient frontier point to an efficient frontier point is maximized (Ali and Seiford, 1993) and thirdly, multi-stage DEA method (Coelli, 1997). Although the multi-stage DEA approach is more computationally demanding, it was chosen because of two advantages it has over the other methods. First, it identifies projected points which have input and output mixes and secondly, it is invariant to units of measurement. More so, a software was used for the calculation. Thus, the computation exponential problem does not apply to this study.

3.4.2 Variable Return to Scale Model and Scale Efficiency

The constant return to scale (CRS) assumption highlighted above is only appropriate when all the DMUs are operating at an optimal level. In order words, the ports produce outputs with similar input to output ratios across the DMU set (Cheon, 2007). However, due to so many external variables, that is not the case for this research. Thus, a variable return to scale (VRS) model is assumed which enables the input to output ratio to diverge with respect to the port sizes. The implication of this is that a VRS model will have more or equal technically efficient DMUs to those in a CRS model. Thus, some inefficient ports under the CRS model will be efficient in the VRS model (figure 4). To model this mathematically, the convexity constraint $N_1'\lambda=1$ be added to the CRS model. Given as;

$$min_{\theta,\lambda}\ \theta, \quad (3.13)$$

$$subject\ to - y_i + Y\lambda \geq 0 \quad (3.14)$$

$$\theta x_i - X\lambda \geq 0 \quad (3.15)$$

$$N_1{}'\lambda \geq 1 \quad (3.16)$$

$$\lambda \geq 0 \quad (3.17)$$

Where N_1 is an N*1 vector of ones. Following the logic of more technically efficient DMUs in a CRS model than a VRS model, other researchers have broken down the technical efficiency of CRS model into two parts; scale efficiency and pure technical efficiency. This can be calculated by conducting both DEA models on a data set and finding the difference between respective technical efficiencies. Mathematically written:

$$TE_{I,CRS} = AP_C/AP \quad (3.18)$$

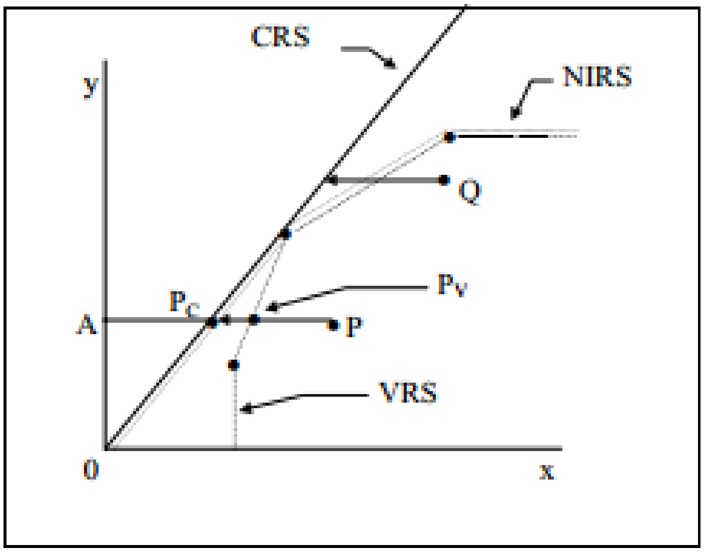
$$TE_{I,VRS} = AP_V/AP \quad (3.19)$$

$$SE_I = AP_C/AP_V \quad (3.20)$$

Where all these measures will be bounded by zero and one. It can also be written as

$$TE_{I,CRS} = TE_{I,VRS} * SE_I \quad (3.21)$$

Figure 4. Scale economies in DEA



3.4.3 Model Orientation

There are two types of orientation that DEA models can be categorized into; input orientation and output orientation. The input-oriented measure focuses on how much input quantities be reduced without changing the output quantities while the output-oriented measures focus on how much the output quantities can be increased while keeping the input quantities constant. It should be noted that the input and output-oriented measures will yield the same technical efficiency when applied on CRS but different measures when applied to VRS (Fare and Lovell, 1978)

The type of problem being modelled determines the orientation measure to be applied. Operation issues align with input orientation while planning and strategies align with output orientation (Cullinane et al., 2005). For this research, the orientation applied is the multiple-output measure which tries to maximize desired output and minimize undesired output while maintaining constant inputs which is the number of berth length, number of gantry cranes, terminal area, investment fund, and policy.

3.4.4. Uncertainty Modelling

As highlighted in the previous section, we chose the DEA model for the benchmarking analysis because of the advantages it has over the other methods. One major strength of DEA is that a prior assumption of the frontier shape and internal workings of the DMUs is not required (Bray et al., 2014). However, this strength can also be a significant weakness because the frontier is constructed based on the assumption that the variable data are accurate. Thus, data sensitivity arises as a weakness.

In reality, observed values for the input and output data are sometimes imprecise or vague which may be a function of incomplete or unquantifiable information (Wanke et al., 2017). To solve this ambiguity, researchers apply uncertainty, and fuzzy logic approaches traditional DEA techniques (Lertworasirikul, 2002; Hatami-Marbini et al., 2011a). There are five categories of fuzzy DEA approaches namely; tolerance approach, alpha-level based approach, fuzzy ranking approach, possibility approach and others (Lertworasirikul et al., 2003; Zhang et al., 2005; Karsak, 2008; Luban. 2009, Zerafat Angiz et al., 2010b).

The tolerance approach aims to incorporate ambiguity into the DEA models by defining the tolerance levels on constraint violations (Sengpta, 1992). The alpha-level based approach aims to convert fuzzy CCR model into a pair of parametric programs in order to find the lower and upper bounds of the alpha-level of the membership functions of the efficiency scores. It is the most popular fuzzy DEA application used (Hatami-Marbini et al., 2011a). In the fuzzy ranking approach, the fuzzy efficiency scores are found using the fuzzy linear programs which require fuzzy sets (Bray et al., 2013). A related method that turns fuzzy variables into crisp values called defuzzification was proposed by Lertworasirikul (2002). The possibility theory fundamentals are built from Zadeh's (1978) fuzzy set theory; possibility of fuzzy events determined using possibility theory. Some of the other methods that cannot be grouped into the four traditional methods highlighted are self-organizing fuzzy (Guo et al., 2000), fuzzy goal DEA (Sheth and Triantis, 2003), Wang et al. (2005) identified a min-max interval approach.

Taking these frameworks into consideration, we decided to incorporate the uncertainty concept into our DEA model to deal with the uncertainty in some of our variables, i.e., environmental policy, investment in technology, accidents, and congestion.

3.5. Proposed DEA models

DEA is applied to evaluate the port's performance while taking into account the proposed dimensions of sustainable development. The DEA models evaluate both undesirable and desirable outputs for ports. Three categories of models are tested namely; ignoring undesirable output, treating undesirable output as input, and directional distance function (section 2.4.2) under variable and constant returns to scale (section 3.4.2). These models will be tested on 13 North American ports in Chapter 4.

3.6. Conclusion

In this chapter, we explored the various research methods for evidence-based study and established our research methodology based on these fundamentals. Subsequently, we identified the indicators that will form the basis of the research as this has a significant impact on the analysis precision. Finally, we deep dived into the DEA model specification to benchmark the selected DMUs and explored uncertainty modeling to handle stochasticity.

Chapter 4

Application

4.1. Introduction

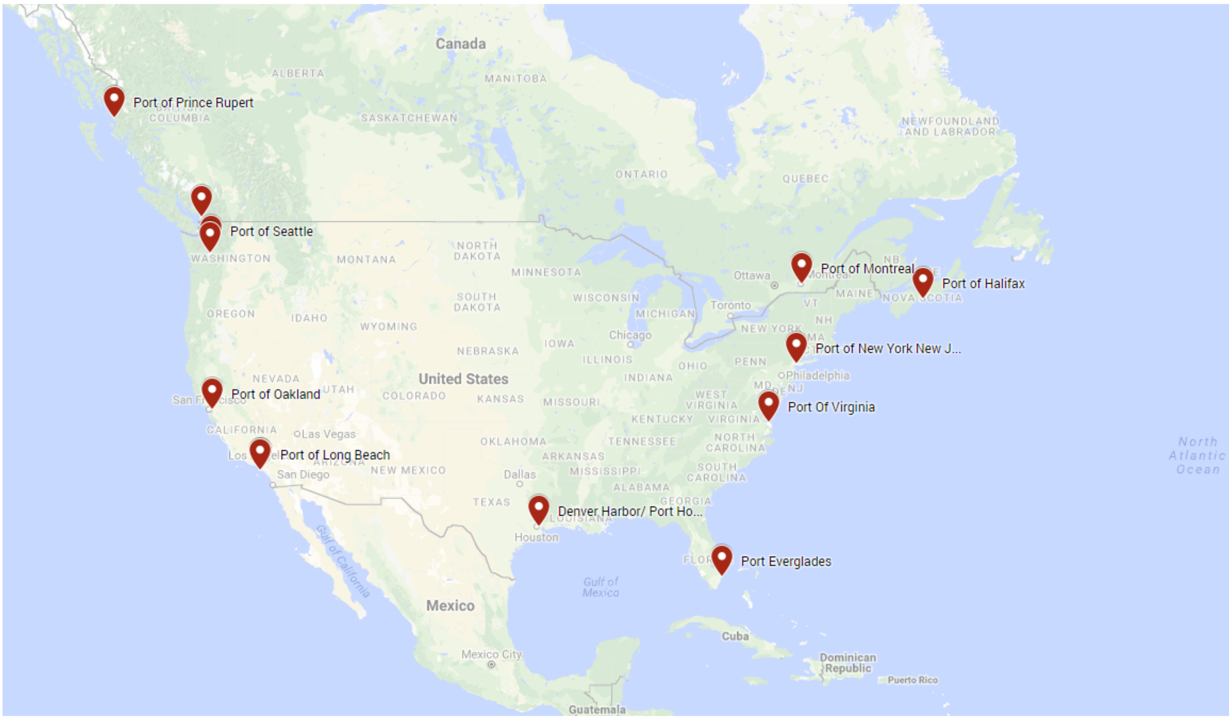
This chapter undertakes the applications of the DEA model which was established in the last chapter. We explore 3 DEA methodologies that address sustainability from different angles.

4.2. Data Description

The container ports for our study were chosen based on literature research, and the availability of data. As shown in Figure 5, the selected ports are located on the North America continent. Four of the ports are Canadian while the rest are in the United States of America. From a size perspective, our analysis cuts across differing port sizes (Figure 5), however, the differences are not outrageous. Relatively speaking, Halifax and Prince Rupert are considered as small-sized ports because they process less than 0.5 million TEUs on an annual basis while Long Beach, Los Angeles, and New Jersey New York are considered the larger ports with annual throughput exceeding 6 million TEUs.

To establish an efficiency ranking, as established in chapter 3, we used three inputs to represent the operational category, and two outputs; one desirable and one undesirable to represent the economic and environmental category. To get comprehensive data, we collected data for these variables across multiple sources; port authority platforms, sustainability reports and independent research firms with a focus on the port industry.

Figure 5. Location of the 13 container ports in North America continent



Source: Google maps

Figure 6. Container ports throughput (TEU) ranking for 2016

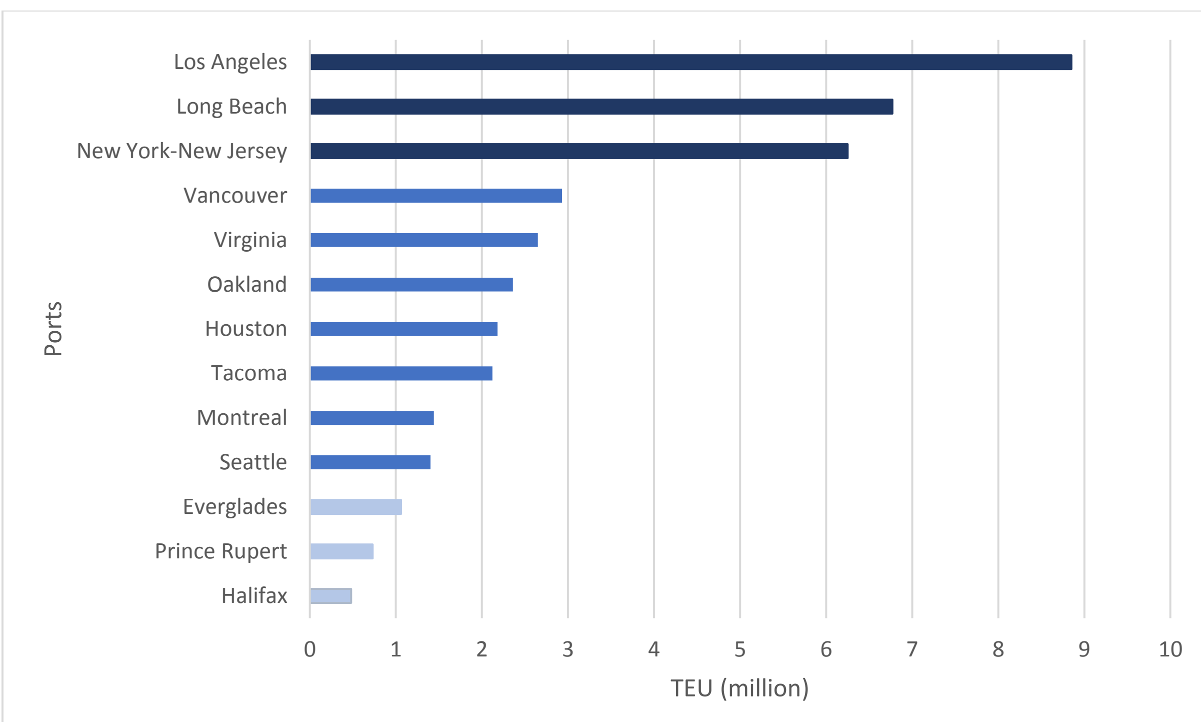


Figure 7. Indicators filtering for sustainability

The correlation and *R-squared* data between the variables are shown in Table 15 and 16 respectively. There is a significant correlation between input and output variables. The input variables have a much stronger correlation with the container throughput than GHG Emissions. Berth length is the least correlated with GHG emissions while number of cranes has the strongest correlation with GHG Emissions. This is plausible since machinery has a direct impact on the GHG emitted to the environment in reality.

Table 13: Indicator value of 13 DMUs (time frame – 2016)

DMU	INUPUT`			OUTPUT	
	Berth Length (m)	Terminal Area (acres)	Number of Cranes	Container Throughput (m TEU)	GHG Emissions (m Tons)
Everglades	6928	316	8	1.06	173623
Halifax	1860	142	12	0.48	35292
Houston	9300	550	22	2.18	1062509
Long Beach	29676	1339	73	6.77	776967
Los Angeles	26812	1693	88	8.85	881496
Montreal	4000	150	17	1.44	66433
New York-New Jersey	27987	1518	69	6.25	1253001
Oakland	22231	780	33	2.36	170405
Prince Rupert	360	60	4	0.73	91000
Seattle	12340	533	21	1.4	47797
Tacoma	10687	594	26	2.12	48060
Vancouver	3067	425	26	2.93	1050593
Virginia	13270	1145	28	2.65	152308

Table 14 Descriptive statistics of port level data

Mean	12962.92	711.15	32.85	3.02	446883.38
Std. dev.	10402.79	545.78	26.57	2.60	473299.44
Min	360.00	60.00	4.00	0.48	35292.00
Max	29676.00	1693.00	88.00	8.85	1253001.00
Skewness	0.53	0.64	1.17	1.33	0.67
Range	29316.00	1633.00	84.00	8.37	1217709.00

Table 15: Correlation between the variables- absolute

	Berth Length	Terminal Area	No. of Cranes	Container Throughput	GHG Emissions
Berth Length	1				
Terminal Area	0.92063	1			
Number of Cranes	0.90310	0.93335	1		
Cont. Throughput	0.84909	0.91732	0.98652	1	
GHG Emissions	0.47449	0.57128	0.63658	0.68332	1

Table 16: R-squared values between the variables

	Berth Length	Terminal Area	No. of Cranes	Container Throughput	GHG Emissions
Berth Length	1				
Terminal Area	0.84756	1			
Number of Cranes	0.81559	0.87115	1		
Cont. Throughput	0.72095	0.84148	0.97322	1	
GHG Emissions	0.22514	0.32636	0.40524	0.46692	1

4.3. DEA Results Analysis

We applied the VRS, and CRS DEA approaches across three of the models highlighted in chapter 2 namely; ignoring undesirable outputs, treating undesirable output as input, and directional distance function approach. Figure 8 shows a bar chart comparing the efficiency score of these three models under the VRS approach while Figure 9 shows the result under the CRS approach. Subsequently, we compared these three models and the efficiency scores calculated from these methods are summarized in Table 17.

Table 17 Efficiency score comparison between three DEA approaches (VRS output oriented)

Ports	Ignoring undesirable outputs	Treating undesirable output as input	Directional distance function
Los Angeles	1	1	1
Montreal	1	1	1
Prince Rupert	1	1	1
Vancouver	1	1	1
Long Beach	0.9406	0.9447	0.9406
Everglades	0.9381	0.9455	0.9381
Virginia	0.8491	1	0.8491
New York-New Jersey	0.8883	0.8883	0.7890
Houston	0.8617	0.8617	0.7425
Tacoma	0.7235	1	0.7235
Oakland	0.6558	0.7934	0.6558
Seattle	0.5761	0.8667	0.5761
Halifax	0.3766	1	0.3766
Mean	**0.8315**	**0.9462**	**0.8147**
No. of Efficient DMU	**4**	**7**	**4**

Figure 8. Eco-efficiency ranking of ports showing the three DEA methods applied on the data set (VRS output oriented)

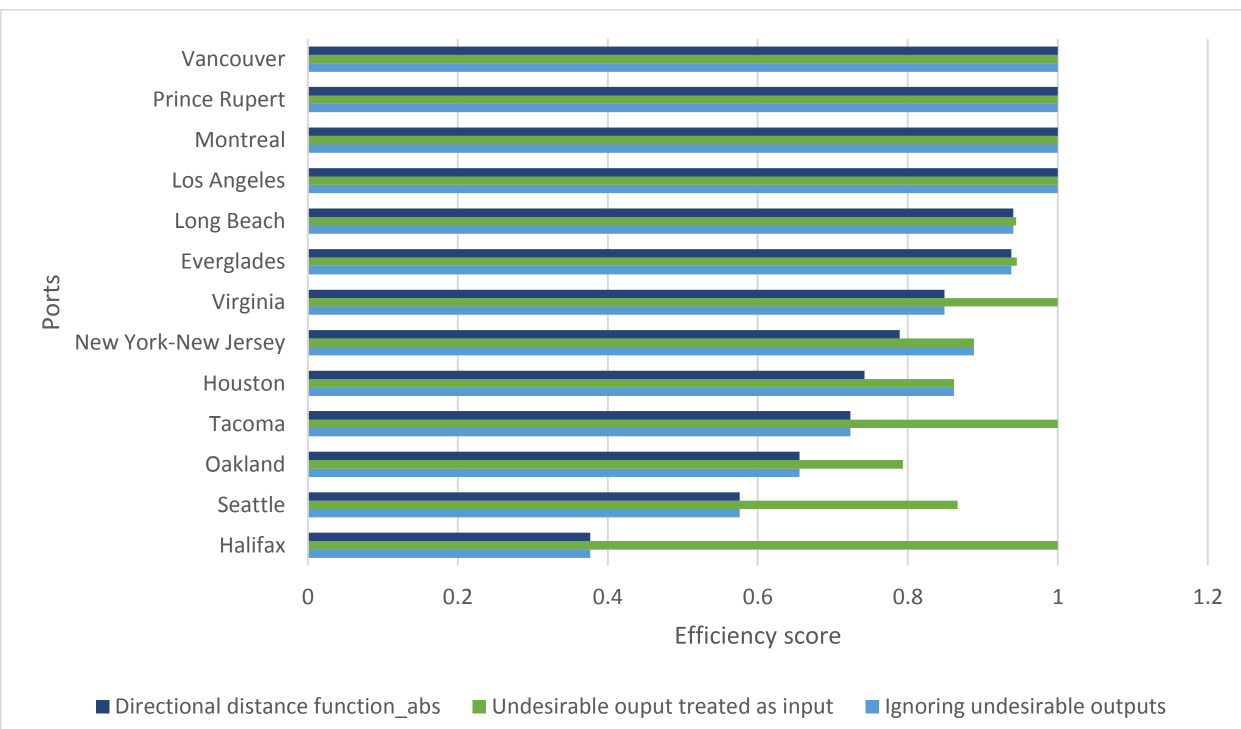
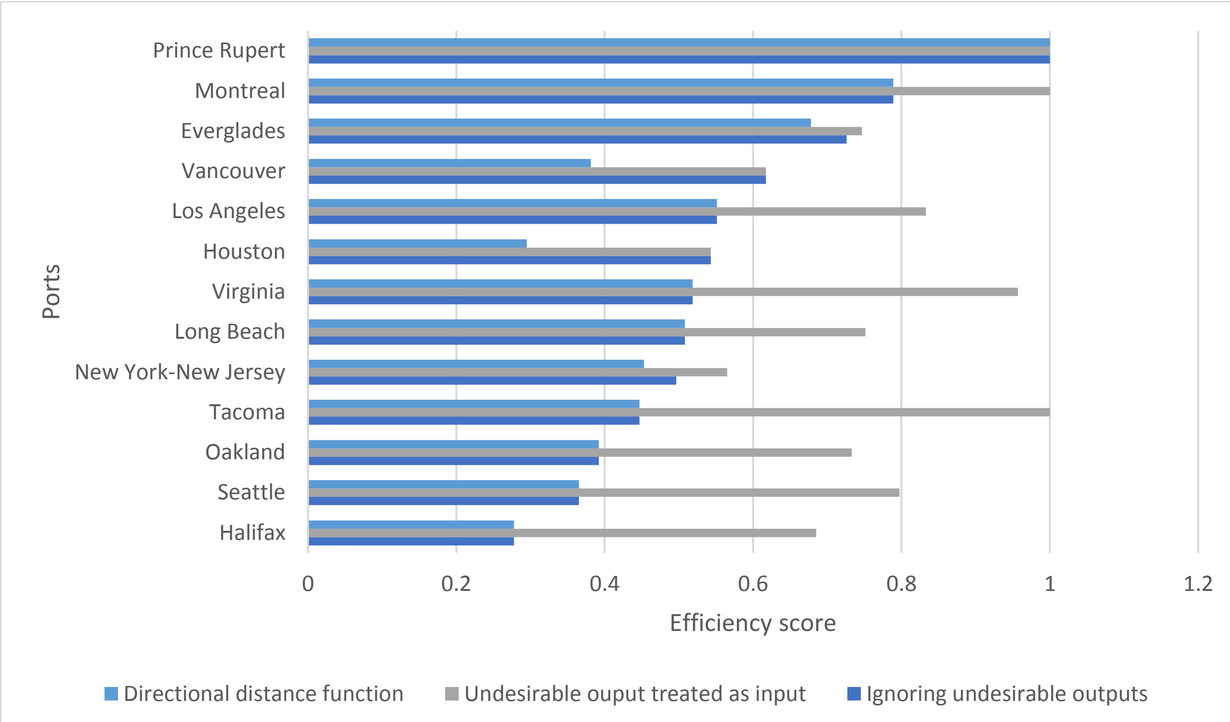


Figure 9. Eco-efficiency ranking of ports showing the three DEA methods applied on the data set (CRS output oriented)



Discussing the DEA methods under the VRS output orientation in Table 17, Ignoring undesirable output translates to 4 DMUs being defined as efficient and a mean efficiency of 0.8315. However, in the second method where the undesirable output was treated as input, 7 DMUs were deemed efficient with a mean of 0.9462 while the directional distance function approach resulted to 4 DMUs as efficient and a mean of 0.8147. Although the ignoring undesirable factors method and directional distance function approaches have the same DMUs deemed as efficient; Los Angeles, Montreal, Prince Rupert and Vancouver, the former method has a higher efficient mean on the average. This higher value may be the result of ignoring undesirable output which does not model the reality of things. From these results, we can see that the first two methods promote better efficiency scores even when undesirable outputs are considered. The implication is that the ports may not be able to pinpoint the effects of sustainability and react accordingly. Thus, the directional distance function is a more plausible method to adopt. Comparison in other sections will be based on the directional distance function.

Table 18 Comparison between three DEA approaches (CRS output oriented)

Ports	**Ignoring undesirable outputs**	**Treating undesirable output as input**	**Directional distance function**
Prince Rupert	1	1	1
Montreal	0.789	1	0.789
Everglades	0.726	0.7467	0.6780
Los Angeles	0.5511	0.8331	0.5511
Virginia	0.5186	0.9571	0.5186
Long Beach	0.5082	0.7515	0.5082
New York-New Jersey	0.4963	0.565	0.4529
Tacoma	0.4468	1	0.4468
Oakland	0.3919	0.7331	0.3919
Vancouver	0.6175	0.6175	0.3813
Seattle	0.3653	0.7974	0.3653
Houston	0.543	0.543	0.2948
Halifax	0.2778	0.6851	0.2778
Mean	**0.5562**	**0.7868**	**0.5119**
No. of efficient DMU	**1**	**3**	**1**

In the CRS orientation as reported in Table 18, fewer DMUs are deemed efficient when compared with the VRS orientation. This can be explained by the CRS principle which is stricter in reporting efficiencies because it reports both technical and scale efficiencies. For instance, only 1 DMU; Prince Rupert port is defined efficient in the ignoring desirable outputs method and the directional distance function while 3 DMUs are deemed efficient when the undesirable output is treated as an input. Although fewer DMUs are identified as efficient, there is some consistency across the DEA approaches which further buttress the insight of applying the directional distance function drawn from the initial orientation.

As mentioned in chapter 3, efficiency can be broken down into pure technical and scale efficiency. From a technical efficiency viewpoint, Table 17 shows that Los Angeles, Montreal, Prince Rupert, and Vancouver are the most efficient relative to others while Long Beach and Everglades are slightly inefficient with relative efficiency scores of 94% and 93% respectively. Consequently, Long Beach needs to improve the amount of TEU processed and decrease the amount of GHG emitted by a total of 7% in order to be considered relatively efficient. This analogy can be applied to the other nine ports defined as technically inefficient. Subsequently, Table 19 shows the scale efficiency values calculated from the CRS and VRS models, as stated mathematically in chapter 3. The overall mean efficiency is calculated as 51%, average pure technical efficiency as 81% and average scale efficiency as 63%. The difference in the mean overall and pure technical efficiency depicts a structural inefficiency in most of the ports especially three out of the four ports that were reported as technically efficient. Prince Rupert port is the only one that is efficient on both fronts. It is also interesting to see that contrary to every other port in our sample space, only Prince Rupert port exhibits a constant return to scale. This means that the throughput and GHG emission increases by the same proportional change as all the inputs.

Table 19 Scale efficiency

Ports	Pure Technical Efficiency _VRS	Overall Efficiency _CRS	Scale Efficiency	RTS of Projected DMU
Prince Rupert	1	1	1	Constant
Montreal	1	0.789	0.789	Decreasing
Los Angeles	1	0.5511	0.5511	Decreasing
Vancouver	1	0.3813	0.3813	Decreasing
Long Beach	0.9406	0.5082	0.5402	Decreasing
Everglades	0.9381	0.6780	0.7228	Decreasing
Virginia	0.8491	0.5186	0.6107	Decreasing
New York-New Jersey	0.7890	0.4529	0.5739	Decreasing
Houston	0.7425	0.2948	0.3970	Decreasing
Tacoma	0.7235	0.4468	0.6175	Decreasing

Oakland	0.6558	0.3919	0.5975	Decreasing
Seattle	0.5761	0.3653	0.6340	Decreasing
Halifax	0.3766	0.2778	0.7376	Decreasing
Mean	0.81	0.51	0.63	
Std. dev	0.1953	0.2055	0.16263	
Correlation (VRS, CRS)	0.6743			

4.3.1 Influence of container throughput on sustainability efficiency

To determine the impact container throughput has on sustainability efficiency, we used the two-tailed t test and Pearson correlation to make some evaluations on the CRS and VRS results versus the container throughput data for respective ports. We tested the following hypothesis:

1. Null hypothesis (H_o): the amount of throughput does not impact the sustainability efficiency of the ports
2. Alternative hypothesis (H_1): throughput has an impact on the sustainability efficiency of the ports

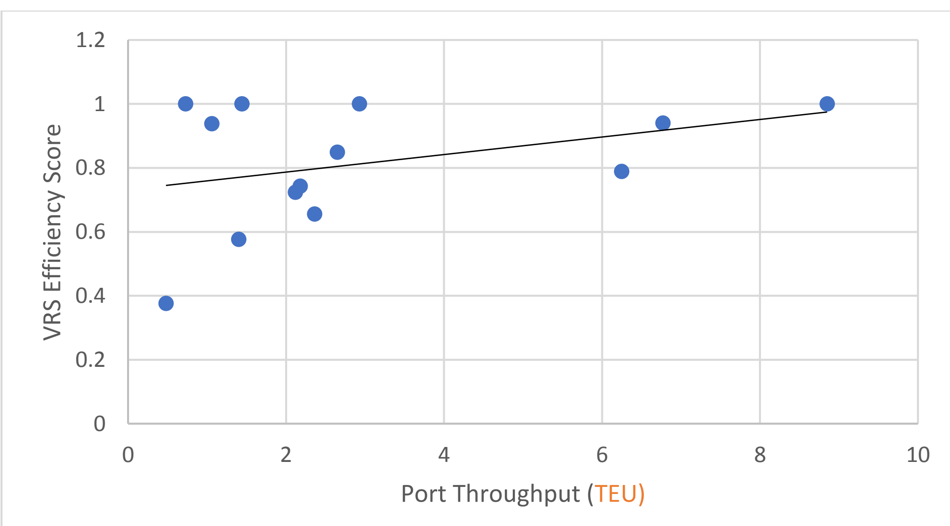
As reported in Table 20, the mean VRS efficiency is 81.4%, and the correlation between the technical efficiency and port throughput is 0.3653. Since the reported alpha level is less than the stated alpha level of 0.05 and the t-stat value of 3.04311 is higher than the one-tail and two-tail t-critical values given as 1.7822 and 2.1788 respectively, we can reject the null hypothesis. This implies that port size has an impact on the sustainability efficiency of ports. Juxtaposing this insight with reality, there is a propensity that larger ports tend to have higher financial capital which can be invested to tackle sustainability challenges either through human capacity to develop and manage relevant sustainability strategies or directly in technology which will act as an enabler to reach desired objectives. However, this assumption should not be taken as absolute. Our analysis was performed on cross-sectional data and needs to be performed over longitudinal data for verification of the analysis.

Consequently, using the directional distance function in VRS model, we found out that all four ports are eco-efficient in both resource and environmental segments; Los Angeles, Montreal, Prince Rupert and Vancouver, however, Houston and New York-New Jersey are relatively more inefficient in the environmental category than the resource-efficiency in comparison to other inefficient ports (Figure 11).

Table 20 Comparison between efficiency scores and ports' throughput

	CRS	*VRS*	*Throughput*
Mean	0.511989	0.814723	3.016923077
Variance	0.042235	0.038158	6.769873077
Observations	13	13	
Pearson Correlation	-0.10841	0.365327	
Hypothesized Mean Difference	0	0	
Degrees of Freedom	12	12	
t Stat	3.460407	3.04311	
P(T<=t) one-tail	0.002357	0.005107	
t Critical one-tail	1.782288	1.782288	
P(T<=t) two-tail	0.004714	0.010215	
t Critical two-tail	2.178813	2.178813	

Figure 10. Relationship between efficiency scores and port size



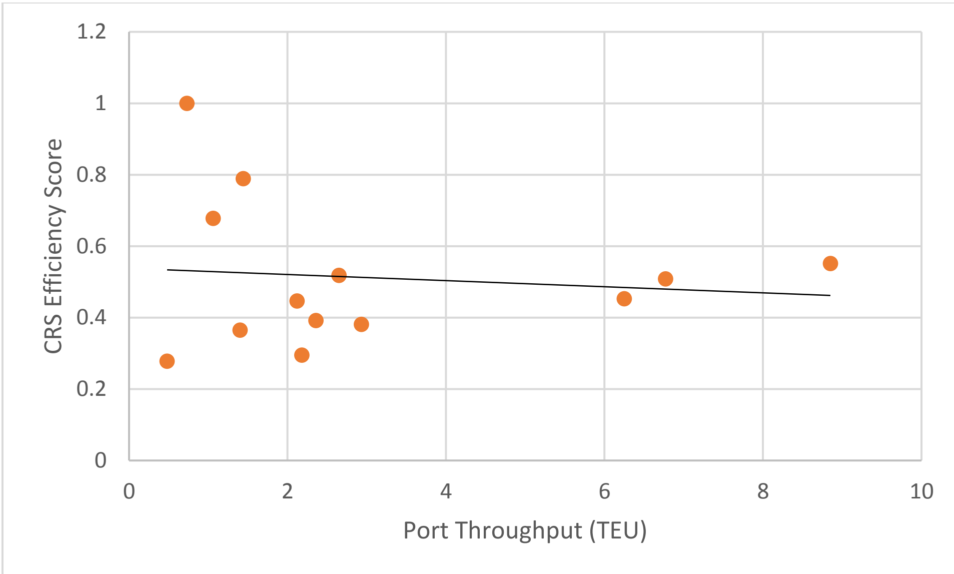
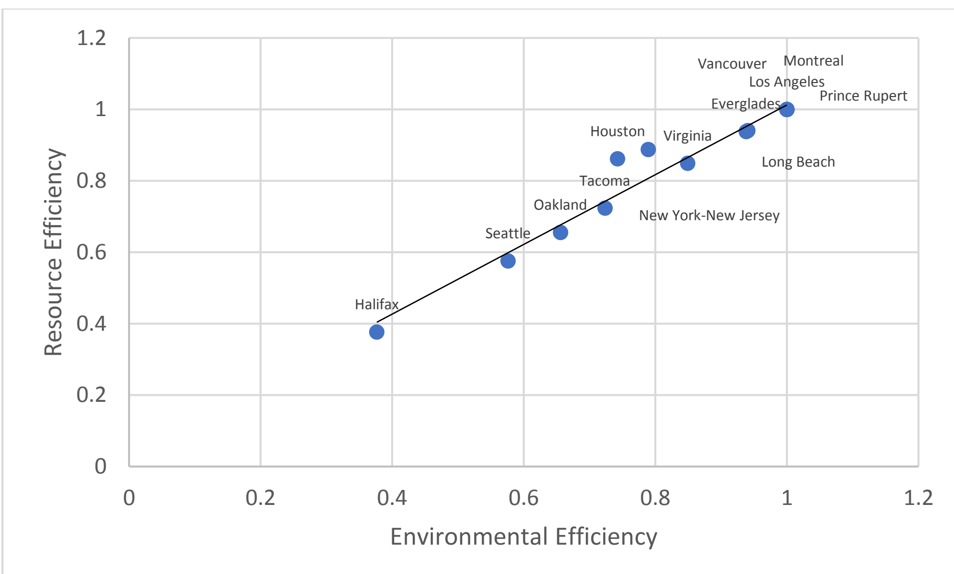


Figure 11. Relationship between environmental efficiency and resource efficiency



4.3.2 Analysis and Recommendations

DEA VRS method enables us to measure the performance improvements with respect to each indicator per port as shown in Table 21.

Table 21: Percentage of improvements required by respective ports to reach the frontier

DMU	Rank	Input			Output	
		Berth Length	Terminal Areas	Number of Cranes	Container Throughput	GHG Emission
Los Angeles	1	Benchmark				
Montreal	1	Benchmark				
Prince Rupert	1	Benchmark				
Vancouver	1	Benchmark				
Long Beach	5	-31.989	0	-3.163	0	0
Everglades	6	-87.699	-60.012	0	0	0
New York-New Jersey	7	-30.199	-14.07	0	0	0
Houston	8	-72.314	-34.793	0	0	0
Virginia	9	-71.116	-59.31	0	0	0
Tacoma	10	-71.302	-28.451	0	0	0
Oakland	11	-74.145	-27.159	0	0	0
Seattle	12	-80.132	-35.826	0	0	0
Halifax	13	0	0	-6.539	0	0

Note: (1) Negative values represent a decrease. (2) Outputs were considered zero because from the output standpoint, only inputs vary.

Apart from Port of Halifax, it is seen that the farther an inefficient port is from the efficient ports, the higher the improvements required across the three inputs. The number of cranes indicator requires the lowest percentage of improvements in only two ports while the berth length requires the highest number of percentage improvements in eight ports. Consequently, improvements to the terminal areas is lowest in Long Beach and Halifax and highest in Everglades and Virginia.

Long Beach needs no improvements to its terminal area and 31% improvement to berth length. Everglades requires no improvements to the number of cranes but 88% in berth length and 60% in terminal area. Similarly, New York-New Jersey, Houston, Virginia. Tacoma, Oakland, and Seattle do not require any improvements in Number of Cranes and the biggest improvement they require is in Berth Length; 30%, 72%, 71%, 71%, 74%, and 80% respectively.

To address the required improvements reported in Table 21, the port management can incorporate particular strategies as presented in Table 22. As indicated in Table 15, there is a high correlation between the three indicators. Therefore, an improvement in one of these indicators can lead to improvement in another.

Table 22 Improvement strategies in ports

Strategy	Suggested short to medium term emission reducing technologies and initiatives	Indicators affected
Productivity and efficiency improvement	Adopted to each ports, however, efforts should streamline human factor errors, scheduling, improve automation, reduce waiting-times and idling	Berth Length, Terminal Area, No. of Cranes
	Replace high emitting engines with lower emitting and higher-efficiency engines for vehicles and equipment	
Operating practices and policies	Improve energy management and efficiency for large powered equipment i.e. gantry cranes	Berth Length, Terminal Area, No. of Cranes
Alternative energy and hybrid technology strategies	Hybrid traditional fuel and electric engine systems for gantry cranes and other vehicles, including OCVs	Berth Length, Terminal Area, No. of Cranes
	Ultra-low Sulphur diesel fuel	

Source: adapted from Levelton (2007)

4.4. Results Validation

To validate the results of our quantitative approach, we cross-checked the top ranking ports with real life scenarios. We found out that our top ranking ports have been recognized by international environmental and sustainability organization in several instances e.g. Port of Montreal, Prince Rupert Port and Port of Vancouver are ranked high in the 2016 Green Marine report. The Green

Marine is a voluntary environmental certification program for North American marine industry. Subsequently in 2012, Port of Los Angeles won the Global Environmental Award by Llyod's List for leadership and environmental initiatives implemented. Lastly, Port of Long Beach received the Clean Air Award by South Coast Air Quality Management District. This recognition is given for its exceptional initiatives to reduce poor air quality in its immediate environment. Table 23 shows a summary of the validated ports.

Table 23 Validation results

Ports	**Proposed Result**	**Green Marine (2016)**	**Environment Excellence Award (2015)**	**Future 40 Responsible Corp. Leaders (2017)**	**Llyod's List Global Award (2012)**	**South Coast Air Quality Mgt District (2016)**
Prince Rupert	1	x				
Montreal	1	x	x			
Los Angeles	1				x	
Vancouver	1	x		x		
Long Beach	0.9406					x

4.5. Conclusion

We provided eco-efficiency of North American container ports using three different DEA methods, namely; ignoring undesirable output, treating undesirable output as input, and directional distance function. Having compared these models, it was established that the directional distance function is the most plausible methodology to benchmark sustainability efficiency of ports within the DEA context because other methods potentially report a higher efficiency value when undesirable variables are taken into consideration. The implication is that port management and relevant stakeholders are blindfolded by this and cannot make the necessary strategic or tactical decisions to improve their sustainability agendas.

Our results show that 30% of the ports in our sample space are eco-efficient and there is a correlation between the effectiveness and efficiency of ports and the eco-efficiency level. Our assumption is that ports with higher levels of productivity tend to have more financial injection towards achieving sustainable development goals since this will give them an edge against their competitors in the industry which further leads to an even better economic return on investments. Similarly, resource efficient ports use the minimum amount of inputs to generate the least amount of undesirable outputs. For instance, we found out there is a relatively high correlation between the number of gantry cranes used and the GHG emitted to the environment. Therefore a potential tactical recommendation will be to invest in the latest gantry crane technology and improve scheduling ocean vessels and terminal area. Interestingly, all four most eco-efficient ports reported in our results are also resource efficient.

Thirdly, there were differences in the results recorded when we compared the BCC and CCR models applied to our analysis. However, this net difference means that the ports are experiencing a structural inefficiency which will be more apparent as they scale unless addressed.

Finally, we faced some limitations when using the DEA methodology. For instance, the methodology requires ample sample size and substantial data for accuracy and reliability, however, we were constrained by data unavailability for more ports. Furthermore, the methodology identifies weights that maximize the efficiency score of the evaluating unit in comparison with a group of similar units or activities. However, some activities may appear as efficient even though they perform well only on a single, relatively unimportant criterion.

Chapter 5

Conclusions & Future Works

5.1. Conclusions

Sustainability development agendas are experiencing growth from a global perspective. In this thesis, we address the problem of benchmarking port sustainability performance. A two-step approach is proposed.

In the first step, we determined indicators to reflect ports sustainability performance. A detailed review of the prior literature was performed, the indicators identified were categorized into three macro dimensions; economic, environmental and social. These indicators were further refined with the help of relevant stakeholders to 10 sub-indicators namely, container throughput, GHG emissions, sewage emissions, congestion, accidents, berth length, terminal area, number of gantry cranes, technology investment fund, and existence of environmental policy.

To measure the port sustainability performance, we applied two DEA methods that focus on minimizing the undesirable attributes of port productivity. Three categories of models are proposed namely; ignoring undesirable output, treating undesirable output as input, and directional distance function under variable and constant returns to scale. We found out that the directional distance function approach is the most plausible because other ways tend to report higher efficiency scores on the average for ports even though adverse effects of productivity were taken into consideration.

The result of our analysis for the 13 selected ports shows that 30% of the ports are technically efficient. The difference in the DEA-BCC and the DEA-CCR indicates the presence of scale inefficiency. However, the efficiency difference experienced by the port can be attributed more towards scale than technical efficiency as seen in the mean efficiency scores of 63% and 81% respectively. From our analysis, four ports are deemed the most efficient ports; Montreal, Vancouver, Prince Rupert and Los Angeles while the least efficient port in Halifax. Although the least most efficient is in Canada, three out of the most efficient ports are also located in Canada, and this can generally be an indication of more favorable environmental policies in Canada than the United States of America. This finding is relatively consistent with the Green Marine 2016 performance report. The report ranks port of Montreal and port of Vancouver as the top ports regarding sustainability.

The average scale inefficiency of the ports is 37% in 2016. The DEA measure shows the direction of improvements in scale efficiency and all ports except Prince Rupert operate under decreasing returns to scale. Since scale inefficiency implies the imprudent use of capital input, this means that the ports are underutilized and it is suggested that the ports need to reduce the number of inputs required to operate at an optimal structural efficiency level. Conversely, there is 19% potential improvement in pure technical efficiency for the average port in our analysis. This indicates misuse of input since technical efficiency is an assessment of adequately appropriating of port inputs to maximizing productivity.

We also investigated the impact that port productivity has on sustainability performance. We found out that there is a correlation between the port size and performance. This may be attributed to the fact that larger ports have access to financial investments that can allow them to employ the required human capacity and technology which in turn makes them efficient. This is in agreement with the mean technical efficiency values. The large ports (Los Angeles and Long Beach) have a mean score of 97% while the smaller ports (Prince Rupert and Halifax) have an average efficiency score of 68%.

5.2. Limitations of the Research

Data gathering is the primary limitation of this research. This restricted the number of ports involved in the DEA methodologies. The implication of this is that a large percentage of the ports reported high-efficiency values, especially in the VRS analysis. Apart from this, fewer attributes were incorporated into the analysis as supposed to the ten attributes that were proposed to reflect the aspects of port sustainability performance. However, the results depict a directional digest of the sustainability performance of the ports in our case analysis.

5.3. Future Works

In this research, we have aimed to benchmark ports sustainability performance by identifying and analyzing indicators through the comparison of three DEA methods over cross-sectional data.

Further work can involve more advanced DEA and statistical techniques to investigate which methods will provide better viable results. Finally, analysis across dynamic and longitudinal time frames can be performed to reveal evolutionary insights over time about the ports.

Bibliography

Almawsheki, E. S., & Shah, M. Z. (2014). Technical efficiency analysis of container terminals in the middle eastern region. *The Asian Journal of Shipping and Logistics, 31*(4), 477-486.

American association of port authorities. Retrieved from http://www.aapa-ports.org/Industry/content.cfm?ItemNumber=1022&navItemNumber=901

Banker, R. D., Charnes, R. F., & Cooper, W. W. (1984). Some models for estimating technical and scale inefficiencies in data envelopment analysis. *Management Science, 30*, 1078-1092.

Barros, C. P., Wanke, P., Nwaogbe, O. R., & Azad, M. A. K. (2017). Efficiency in Nigerian airports. *Case Studies on Transport Policy, 5*(4), 573-579. doi:https://doi.org/10.1016/j.cstp.2017.10.003

Bendall, H., & Stent, A. (1987). On measuring cargo handling productivity. *Maritime Policy and Management, 14*(4), 337-343.

Bergmans, A., Vandermoere, F., & Loots, I. (2014). Co-producing sustainability indicators for the Port of Antwerp. *ESSACHESS - Journal for Communication Studies, 7*(1), 107-124.

Bichou, K., & Gray, R. (2005). A critical review of conventional terminology for classifying seaports. *Transportation Research Part A: Policy and Practice, 39*(1), 75-92. doi:https://doi.org/10.1016/j.tra.2004.11.003

Black, W. R. (1996). Sustainable transportation: A US perspective.*4*(3), 151-159.

Bray, S., Caggiani, L., Dell'Orco, M., & Ottomanelli, M. (2014). Features selection based on fuzzy entropy for data envelopment analysis applied to transport systems. *Transportation Research Procedia, 3*, 602-610. doi:https://doi.org/10.1016/j.trpro.2014.10.039

Bray, S., Caggiani, L., Dell'Orco, M., & Ottomanelli, M. (2014). Measuring transport systems efficiency under uncertainty by fuzzy sets theory based data envelopment analysis. *Procedia - Social and Behavioral Sciences, 111*, 770-779. doi:https://doi.org/10.1016/j.sbspro.2014.01.111

Bruntland, G. (1987). Our common future: The world commission on environment and development. *Oxford University Press*

Bureau of transportation statistics., January 3, 2018.

American trucking associations, the city of Los Angeles; the harbor department of the city of Los Angeles, (California 2011). Retrieved from http://cdn.ca9.uscourts.gov/datastore/opinions/2011/09/26/10-56465.pdf

Chen, Z., & Pak, M. (2017). A delphi analysis on green performance evaluation indices for ports in china. *Maritime Policy and Management, 44*(5), 537-550. doi:10.1080/03088839.2017.1327726

Cheon, S., & Deakin, E. (2010). Supply chain coordiantion for port sustainability. *Journal of Transportation Research Board,* , 10-19. doi:10.3141/2166-02

Collis, J., Hussey, R., Crowther, D., Lancaster, G., Saunders, M., Lewis, P., . . . Gill, J. (2003). *Business research methods*. New York: Palgrave Macmillan.

Cook, W. D., Seiford, L. M., & Zhu, J. (2013). Data envelopment analysis: The research frontier. *Omega, 41*(1), 1-2. doi:https://doi.org/10.1016/j.omega.2012.01.011 "

Creswell, J. W. (1994). *Research design: Qualitative and quantitative approaches.* USA: SAGE Publications, Incorporated.

Cullinane, K., & Wang, T. (2006). Chapter 23 data envelopment analysis (DEA) and improving container port efficiency. *Research in Transportation Economics, 17*, 517-566. doi:https://doi.org/10.1016/S0739-8859(06)17023-7

Cullinane, K., Wang, T., Song, D., & Ji, P. (2006). The technical efficiency of container ports: Comparing data envelopment analysis and stochastic frontier analysis. *Transportation Research Part A: Policy and Practice, 40*(4), 354-374. doi:https://doi.org/10.1016/j.tra.2005.07.003

Davarzani, H., Fahimnia, B., Bell, M., & Sarkis, J. (2016). Greening ports and maritime logistics: A review. *Transportation Research Part D: Transport and Environment, 48*, 473-487. doi:https://doi.org/10.1016/j.trd.2015.07.007

Debreu, G. (1951). The coefficient of resource utilization. *Econometrica: Journal of the Econometric Societu,* , 273-292.

Deprins, D., & Simar, L. (1983). On farell measures of technical efficiency. *Recherches Economiques De Louvain, 49*(2), 123-137.

Donnelly, A., Jones, M., O'Mahony, T., & Byrne, G. (2007). Selecting environmental indicator for use in strategic environmental assessment. *Environmental Impact Assessment Review, 27*(2), 161-175. doi:https://doi.org/10.1016/j.eiar.2006.10.006

Dyckhoff, H., & Allen, K. (2001). Measuring ecological efficiency with data envelopment analysis (DEA). *European Journal of Operational Research, 132*, 312-325.

Emily Guerin. (2017). How local ports reduced pollution but lost trust among truck drivers along the way. Retrieved from https://www.scpr.org/news/2017/03/13/69667/how-local-ports-reduced-pollution-but-lost-trust-a/

ESPO (European Sea Ports Organisation). (2017). *Sustainability report*. Retrieved from https://www.ecoports.com/assets/files/common/publications/2017_11_08_Sustainability_report_2017_Review_final.pdf

Fa¨re, R., Grosskopf, S., & Hernanadez-Sancho, F. (2004). Environmental performance: An index number approach. *Resource and Energy Economics,* (26), 343-352.

Farrell, M. J. (1957). The measurement of productivity efficiency. *Journal of Royal Statistical Society, 120*(3), 253-290.

Ferrari, C., Puliafito, P. P., & Tei, A. (2013). Performance and quality indexes in the evaluation of the terminal activity: A dynamic approach. *Research in Transportation Business and Management, 8*, 77-86.

Ferretti M., Parmentola A., Parola F., Risitano M. (2017). Strategic monitoring of port authorities activities: Proposal of a multi-dimensional digital dashboard. *Production Planning and Control, 28*(16), 1354-1364. doi:10.1080/09537287.2017.1375146

Galbraith, V., Curry, L., & Loh, C. (2008). *Green harbours: Hong kong & shenzhen reducing marine and port-related emissions*. Hong Kong, People's Republic of China: Civic Exchange. Retrieved from http://doc.mbalib.com/view/ 28490eb7804bad7a82924ad4c3cd969c.html

Golany, B., & Roll, Y. (1989). An application procedure for DEA. *Omega,* (17), 237-250.

Gonzalez, M. M., & Trujillo, L. (2008). Reforms and infrastructure efficiency in Spain's container ports. *Transportation Research Part A,* (42), 243-257.

Green marine 2016 performance report. Retrieved from https://www.green-marine.org/wp-content/uploads/2017/05/2016_Performance_Report.pdf

Greene, W. (1993). In Fried H., Lovell C. A. K. and Schmidt S. (Eds.), *The econometric approach to efficiency measurement*. New York: Oxford University Press.

Greentech 2017. (2017). (2017). Paper presented at the Fort Lauderdale, Florida. Retrieved from https://www.green-marine.org/2017/03/27/greentech-2017-preliminary-program-unveiled/

Guimaraes, V. A., Juniorb, I. C. L., & Garcia, P. A. A. (2014). Environmental performance of brazilian container terminals; A data envelopment analysis approach. *Social and Behavioral Sciences, 160*, 178-187.

Hai-bo, K., & He-Zhong, L. (2009). Research on X-efficiency measure of Chinese ports. *System Engineering - Theory 7 Practice, 29*(2), 1-9.

Haralambides, H., & Gujar, G. (2012). On balancing supply chain efficiency and environmental impacts: An eco-DEA model applied to the dry port sector of India. *Maritime Economics & Logistics, 14*, 122-137. doi:10.1057/mel.2011.19

Haralambides, H., & Gujar, G. (2011). The Indian dry ports sector, pricing policies and opportunities for public-private partnerships. *Research in Transportation Economics, 33*(1), 51-58. doi:https://doi.org/10.1016/j.retrec.2011.08.006

Hatami-Marbini, A., Emrouznejad, A., & Tavana, M. (2011). A taxonomy and review of the fuzzy data envelopment analysis literature: Two decades in the making. *European Journal of Operational Research, 214*(3), 457-472. doi:https://doi.org/10.1016/j.ejor.2011.02.001

Holdsworth, J. (2004). The merging of community sustainability with enhanced environmental performance: A local government case study. *Advances in Architecture Series, 18*, 495-504.

Hou, L., & Geerlings, H. (2016). Dynamics in sustainable port and hinterland operations: A conceptual framework and simulation of sustainability measures and their effectiveness, based on an application to the port of shanghai. *Journal of Cleaner Production, 135*, 449-456. doi:10.1016/j.jclepro.2016.06.134

Hung, S. W., Lu, W. M., & Wang, T. P. (2010). Benchmarking the operating efficiency of Asia container ports. *European Journal of Operational Research 203,* , 706-713.

ISO (International Organisation for Standardisation). (1999). *Environmental performance evaluation - guidelines.* (No. ISO 14031:1999).

Jakosbsen, S. (2008). Environmental indicators. the encyclopedia of earth. Retrieved from https://editors.eol.org/eoearth/wiki/Environmental_indicators

Jiang, B., & Li, J.,. (2009). DEA-based performance measurement of seaports in northeast asia: Radial and non-radial approach. *The Asian Journal of Shipping and Logistics, 25*(2), 219-236.

Jiang, X., Chew, E. P., & Lee, L. H. (2015). Innovative container terminals to improve global container transport chains. *International Series in Operations Research and Management Science, 220*, 3-41. doi:10.1007/978-3-319-11891-8_1

Jusoh, L. S., Hashim, H., Lim, J. S., & Mansor, N. N. A. (2017). Framework for greenhouse gas accounting towards green port. *Chemical Engineering Transactions, 56*, 685-690. doi:10.3303/CET1756115

Kilkiş, Ş. (2015). Composite index for benchmarking local energy systems of mediterranean port cities. *Energy, 92*(Part 3), 622-638. doi:10.1016/j.energy.2015.06.093

Kisi, H., & Zorba, Y. (1999). Assessment of port performance: Application on port of Izmir. In M. Kalkan (Ed.), *Strategic approaches for maritime industries in Poland and Turkey* ()

Koopmans, T. C. (1951). (1951). An analysis of production as an efficient combination of activities. Paper presented at the *Activity Analysis of Production and Allocation,* New York.

Korhonen, P. J., & Luptacik, M. (2004). Eco-efficiency analysis of power plants: An extension of data envelopment analysis. *European Journal of Operational Research, 154*(2), 437-446. doi:https://doi.org/10.1016/S0377-2217(03)00180-2

Krauss, S. E. (2005). Research paradigms and meaning making: A primer. *The Qualitative Report, 10*(4), 758-770.

Kutin, N., Nguyen, T. T., & Vallée, T. (2017). Relative efficiencies of ASEAN container ports based on data envelopment analysis. *The Asian Journal of Shipping and Logistics, 33*(2), 67-77. doi:https://doi.org/10.1016/j.ajsl.2017.06.004

Kuznetsov, A., Dinwoodie, J., Gibbs, D., Sansom, M., & Knowles, H. (54). Towards a sustainability management system for smaller ports. *Marine Policy,* , 59-68. doi:10.1016/j.marpol.2014.12.016

Lee, K. -., & Wu, Y. (2014). Integrating sustainability performance measurement into logistics and supply networks: A multi-methodological approach. *British Accounting Review, 46*(4), 361-378. doi:10.1016/j.bar.2014.10.005

Leornard, P. (1990). Les indicateurs de la politique maritime (caen, France: Ed. paradigme).

Lertworasirikul, S., Fang, S., A. Joines, J., & L.W. Nuttle, H. (2003). Fuzzy data envelopment analysis (DEA): A possibility approach. *Fuzzy Sets and Systems, 139*(2), 379-394. doi:https://doi.org/10.1016/S0165-0114(02)00484-0

Li, D., Luan, W., & Pian, F. (2013). The efficiency measurement of coastal container terminals in china. *Journal of Transportation Systems Engineering and Information Technology, 15*(5), 10-15.

Lim, S., Bae, H., & Lee, L. H.A study on the selection of benchmarking paths in DEA. *Expert Systems with Applications 38,* , 7665-7673.

Linder, A. (2017). Explaining shipping company participation in voluntary vessel emission reduction programs. *Transportation Research Part D: Transport and Environment, 61*(Part B), 234-245. doi:https://doi.org/10.1016/j.trd.2017.07.004

Lirn, T., Wu, Y. J., & Chen, Y. J. (2012). Green performance criteria for sustainable ports in asia. *International Journal of Physical Distribution and Logistics Management, 43*(5/6), 427-451. doi:10.1108/IJPDLM-04-2012-0134

Liu, Z. (1995). The comparative performance of public and private enterprises. *Journal of Transport Economics,* (29), 263-274.

Lovell, C. A. K., & Eeckaut, P. V. (1993). Frontier tales: DEA and DH. *Mathematical Modeling in Economics,* , 446-457.

Lozano, S., Villa, G., & Canca, D. (2011). Application of centralized DEA approach to capital budgeting in Spanish ports. *Computer and Industrial Engineering 60,* , 455-465.

Lu, W. -., & Lo, S. -. (Journal of the Operational Research Society). A benchmark-learning roadmap for regional sustainable development in china. *2007a,* (58), 841-849.

Lun Y.H.V. (2013). Green management practices and firm performance: A case of container terminal operations. *International Journal of Physical Distribution and Logistics Management, 55*(6), 559-566. doi:10.1016/j.resconrec.2010.12.001

Morales-Fusco, P., Saurí, S., Lekka, A. M., & Karousos, I. (2016). Assessing customs performance in the mediterranean ports. KPI selection and best practices identification as part of the MEDNET project. *Transportation Research Procedia, 18*, 374-383. doi:10.1016/j.trpro.2016.12.049

Nakashima, K., Nose, T., & Kuriyama, S. (2006). A new approach to environmental-performance evaluation. *International Journal of Production Research, 44*, 4137-4143.

Nathnail, E., Gogas, M., & Adamos, G. (2016). Urban freight terminals: A sustainability cross-case analysis. *Transportation Research Procedia,* , 394-402. doi:10.1016/j.trpro.2016.11.037

Notteboom, T., Coeck, C., & Van Den Broeck, J. (2000). Measuring and explaining the relative efficiency of container terminals by means of bayesian stochastic frontier models. *Maritime Economics & Logistics, 2*(2), 83-106.

Panayides, P. M., Maxoulis, C. N., Wang, T., & Ng, K. Y. A. (2009). A critical analysis of DEA applications to seaport economic efficiency measurement. *Transport Reviews, 29*(2), 259-278.

Perera, M. P. A., & Abeysekara, B.Defining KPIs to measure eco-sustainable performance at container terminals in Sri Lanka. *2nd International Moratuwa Engineering Research Conference, MERCon 2016,* , 315-320. doi:10.1109/MERCon.2016.7480160

Peris-Mora, E., Orejas, J. M. D., Subirats, A., Ibáñez, S., & Alvarez, P. (2005). Development of a system of indicators for sustainable port management. *Marine Pollution Bulletin, 50*(12), 1649-1660. doi:https://doi.org/10.1016/j.marpolbul.2005.06.048

Port of Antwerp. (2018). Retrieved from http://www.portofantwerp.com/en

Port of Antwerp statistics., January 6, 2018.

Port of Antwerp sustainability report. (2017). , February 15, 2018.

Port of Halifax facilities., February 6, 2018.

Port of Long Beach. Retrieved from http://www.polb.com/

Port of Long Beach wins SCAQMD clean air award. Retrieved from http://polb.com/civica/filebank/blobdload.asp?BlobID=13921

Port of Long Beach air emission inventory 2016., February 18, 2018.

Port of Long Beach clean air action plan., February 25, 2018.

Port of Los Angeles. Retrieved from https://www.portoflosangeles.org/

Port of Los Angeles. (2012). Llyod's list - global environmental award. Retrieved from http://lloydslistawards-global.com/2012-winners/

Port of Los Angeles air emission inventory 2016., February 8, 2018.

Port of Montreal. Environmental excellence award (2015). Retrieved from https://www.port-montreal.com/en/awards.html

Port of Montreal. (2018). Retrieved from https://www.port-montreal.com/en/

Port of Montreal infrastructure data sheet., February 7, 2018.

Port of New York-New Jersey. (2018). Retrieved from http://www.panynj.gov/port/

Port of New York-New Jersey emission inventory., February 8, 2018.

Port of Oakland. (2018). Retrieved from https://www.portofoakland.com/

Port of Oakland air emission inventory 2016., February 8, 2018.

Port of Oakland habitat initiative., February 25, 2018.

Port of Rotterdam. (2018). Retrieved from https://www.portofrotterdam.com/en

Port of Seattle and Tacoma implementation report., January 15, 2018.

Port of Vancouver. (2017). Future 40 responsible corporate leaders. Retrieved from https://www.portvancouver.com/news-and-media/news/vancouver-fraser-port-authority-recognized-as-a-leader-in-sustainability-by-corporate-knights-for-fourth-year-in-a-row/

Port of Vancouver. (2018). Retrieved from https://www.portvancouver.com/

Port of Vancouver Air Emission Inventory 2015., February 8, 2018.

Port of Vancouver EcoAction program., February 26, 2018.

Port of Virginia sustainability report. (2017). , February 15, 2018.

PPRISM. (2012). Port performance indicators: Selection and measurement (PPRISM). *Project Executive Report,*

Puig, M., Pla, A., Seguí, X., & Darbra, R. M. (2017). Tool for the identification and implementation of environmental indicators in ports (TEIP). *Ocean & Coastal Management, 140*, 34-45. doi:https://doi.org/10.1016/j.ocecoaman.2017.02.017

Puig, M., Wooldridge, C., & Darbra, R. M. (2014). Identification and selection of environmental performance indicators for sustainable port development. *Marine Pollution Bulletin, 81*(1), 124-130. doi:https://doi.org/10.1016/j.marpolbul.2014.02.006

Roh, S., Thai, V. V., & Wong, Y. D. (2016). Towards sustainable ASEAN port development: Challenges and opportunities for Vietnamese ports. *The Asian Journal of Shipping and Logistics, 32*(2), 107-118. doi:https://doi.org/10.1016/j.ajsl.2016.05.004

Roll, Y., & Hayuth, Y. (1993). Port performance comparison applying data envelopment analysis (DEA). *Maritime Policy and Management, 20*(2), 153-161. doi:10.1080/03088839.2016.1274833

Saunders, M., Lewis, P., & Thornhill, A. (2009). *Research methods for business students* (5th ed.). London: Pearson Education, Limited.

Schipper, C. A., Vreugdenhil, H., & De Jong, M. P. C. (2017). A sustainability assessment of ports and port-city plans: Comparing ambitions with achievements. *Transportation Research Part D: Transport and Environment, 57*, 84-111. doi:10.1016/j.trd.2017.08.017

Seiford, L. M., & Zhu, J. (2002). Modeling undesirable factors in efficiency evaluation. *European Journal of Operational Research,* (142), 16-20.

Sharma, M. J., & Yu, S. J.Benchmark optimization and attribute identification for improvement of container terminals. *European Journal of Operational Research 201,* , 568-580.

Tadic, D., Aleksic, A., Popovic, P., Arsovski, S., Castelli, A., Joksimovic, D., & Stefanovic, M. (2017). The evaluation and enhancement of quality, environmental protection and seaport safety by using FAHP. *Natural Hazards and Earth System Sciences, 17*(2), 261-275. doi:10.5194/nhess-17-261-2017

Thomas, B. J., & Monie, G. (2000). The measurement of port performance with particular reference 10 container terminal operations. *International Labour Organization 'S (Ilo 'S) Port'Orker Development Programme (Pdp). Cardiff/ Antwerp,*

Tongzon, J. (2001). Efficiency measurement of selected Australian and other international ports using data envelopment analysis. *Transportation Research Part A: Policy and Practice, 35*(2), 107-122. doi:https://doi.org/10.1016/S0965-8564(99)00049-X

Trujillo, L., & Nombela, G. (1999). Privatization and regulation of the seaport industry. *Policy Research Working Paper,* (2181), 48-50.

Tulkens, H., & Eeckaut, P. V. (1995). Non-parametric efficiency, progress and regress measures for panel data: Methodological aspects. *European Journal of Operational Research 80,* , 474-499.

Ueda, E., Thiessen, D., Yaffe, D., & Taylor, T. (2007). (2007). Portwide storm water pollution prevention and dust control program. Paper presented at the *11th Triennial International Conference on Ports,* San Diego CA, United States.

UNCTAD. (1976). (1976). Port performance indicators. Paper presented at the *United Nations Conference on Trade and Development,* New York, US.

Walker, T. R. (2016). Green marine: An environmental program to establish sustainability in marine transportation. *Marine Pollution Bulletin, 105*(1), 199-207. doi:https://doi.org/10.1016/j.marpolbul.2016.02.029 "

Wilson, A., Johns, R., Miller, K. W., & Pentecost, R. (2010). *Marketing research: An integrated approach: Solving business problems: The value of marketing research* (3rd ed.). Australia: Frenchs Forest, N.S.W.: Pearson.

Yang, H., & Politt, M. (2010). The necessity of distinguishing weak and strong disposability among undesirable outputs in DEA: Environmental performance of Chinese coal fired plants. *Energy Policy, 38*(8), 4440-4444.

Yo¨ru¨k, B. K., & Zaim, O. (2008). International regulations and environmental performance. *Applied Economics,* (40), 807-822.

Zhang, B., Bi, J., Fan, Z., Yuan, Z., & Ge, J. (2008). Eco-efficiency analysis of industrial system in china: A data envelopment analysis approach. *Ecological Economics, 68*(1), 306-316. doi:https://doi.org/10.1016/j.ecolecon.2008.03.009

Zhou, P., Ang, B. W., & Poh, K. L. (2007). A mathematical programming approach to constructing composite indicators. *Ecological Economics,* (62), 291-297.