Designing Smart Ports by Integrating Sustainable Infrastructure and Economic Incentives

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Dedicated to

my beloved Navid,

my dear parents Aghdas and Aman,

and my precious sisters Nasim and Neda

with all my love

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Abstract

Ports and harbors are facing stiff competition for market share and delivering more effective and secure flow of goods worldwide. High performing ports are implementing smart technologies to better manage operations meeting new challenges in maintaining safe, secure, and energy efficient facilities that mitigate environmental impacts. Key elements and associated challenges in the ports include operations (e.g., congestion, delays, operating errors, and lack of information sharing), environment (e.g., air, water and noise pollution, waste disposal, construction and expansion activities), energy (e.g., increasing energy consumption, increasing energy costs, and energy disruption impacts on the port activities), safety (e.g., berthing impacts, vessel collisions, and striking while at berth), and security (e.g., armed robbery, cyber security issues, unlawful acts, stowaways, drug smuggling, use of ports as conduit for moving weapons and terrorist attacks). In response to the existing problems, ports are adopting technology-based solutions, as well as new approaches to port operations planning and management. The implementation of such solutions to mitigate recent problems is known to be switching to smart ports. Although there are ongoing smart port initiatives around the world, a unified definition of a smart port has not been well documented.

The proposed research attempts to conceptualize and define smart ports and enable them through the integration of sustainable infrastructure such as microgrids and onshore power supply. As defined by the Department of Energy (DOE), a microgrid is a relatively small-scale localized energy network that features an effective integration of high penetration level of Distributed Energy Resources (DERs), such as renewable energy resources, energy storage devices, and controllable loads.

As the first contribution, we attempt to develop a framework for a smart port and a quantitative metric, *Smart Port Index (SPI)*, that ports can use to improve their resiliency and sustainability. Our proposed SPI is based on Key Performance Indicators (KPIs) gathered from the literature. These KPIs are organized around four key activity domains of a smart port: operations, environment, energy, and safety and security. Case studies are conducted to show how one can use SPI and to assess the performance of some of the busiest ports in the world. Our methodology provides a quantitative tool for port authorities to develop their smart port strategies, assess their smartness,

and identify strengths and weaknesses of their current operations for continuous improvement. Our study reveals that smart port initiatives around the world have different levels of comprehensiveness. The results of this study also suggest that government policies and region-specific variables can impact SPI value.

The second contribution presents a systematic framework for evaluating the benefits of microgrid integration for industrial ports. Ports are critical infrastructure with significant power demands and emission reduction goals. These features make them the ideal candidates for exploring the opportunities that microgrids can offer. We demonstrate how a set of modified Smart Port Index (SPI) metrics can be incorporated into the port microgrid planning process to holistically improve the smartness of the port. A two-stage stochastic mixed-integer model was developed to evaluate the effectiveness of the proposed approach under operation uncertainties. The proposed model consists of an investment master problem in the first stage and a multi-objective operation planning subproblem in the second stage. Benders decomposition has been implemented for solving the stochastic model, and Lexicographic Goal Programming is applied to the subproblem to deal with multiple objectives in the model. Case studies were performed to evaluate the effectiveness of the proposed approach in enhancing major activity domains of a port. Numerical results indicate that compared with the minimum cost planning approach, the proposed framework is capable of improving the productivity, sustainability, and reliability of the port operations. This contribution also studies the investment and planning of onshore power supply (OPS) at port microgrids and analyzes and evaluates the benefits of OPS integration in improving port sustainability and energy efficiency. We show how OPS can be installed and planned along with the microgrids at ports to provide clean power to the vessels at berth. Numerical results illustrate that the integration of OPS along with port microgrid noticeably reduces emissions from the port activities without hindering the economics and competitiveness of the port entity.

The last part of this dissertation studies ports' sustainable development and economic incentives that are designed for this purpose. To promote sustainability strategies and technologies at ports, policy-makers have introduced the concept of regulations and economic incentives. In this contribution, we analyze the process in which a regulatory authority defines regulations, incentives, and tax policies to motivate one or more ports in the region to initiate energy sustainability and emission-reduction efforts. We model the behaviors of both the regulatory authority and the participating ports in the form of a multi-objective mixed-integer nonlinear bilevel optimization problem to capture the hierarchy of the policy-making process and the existing competitions among the ports. The proposed model finds the optimal incentive and tax policies for the policy-maker in the upper-level and provides the ports in the region with the optimal choice of smart and sustainable energy solutions and service prices in the lower-level. Simulation results show that the proposed approach can effectively reduce the region-wide emission due to port activities while ensuring port entities' welfare, competitiveness, and sustainable growth as regional energy hubs.

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Chapter 1

Introduction

1.1 Background

A port is a maritime facility which comprises equipment (e.g., wharf cranes and rubber gantry cranes) and space (e.g., storage yard and parking) required for loading, unloading, and moving cargo and passengers. Early ports acted mostly as simple harbors while modern ports are regional multimodal intersections of global supply chains and tend to be distribution hubs with transportation links to sea, river, canal, road, rail, and air (Figure 1.1). These modern ports function in the context of complex infrastructure, business transactions, and regulations and have a broad range of stakeholders including but not limited to port operators, port authorities, haulers, and shipping companies. There is a recent trend in the ports toward adopting technology-based solutions as well as new approaches to port operations planning and management. Ports are becoming increasingly interested in smart solutions to optimize operations, promote efficiency, enhance sustainability, and avoid safety and security incidents. The implementation of such solutions to mitigate recent problems is known to be switching to smart ports.

There are two categories of solutions that ports are adopting, one approach is more technology-based and involves the improvement of physical infrastructure (e.g., onshore power supply for vessels, electric trucks, electric rubber gantry cranes, hybrid electric rail, automation, and etc) while the other one emphasizes more on the enhancement of policies, ideas, and smart use of current resources (e.g., speed optimization and idling reduction of trucks, vessels scheduling and berth optimization, cargo handling equipment routing optimization).

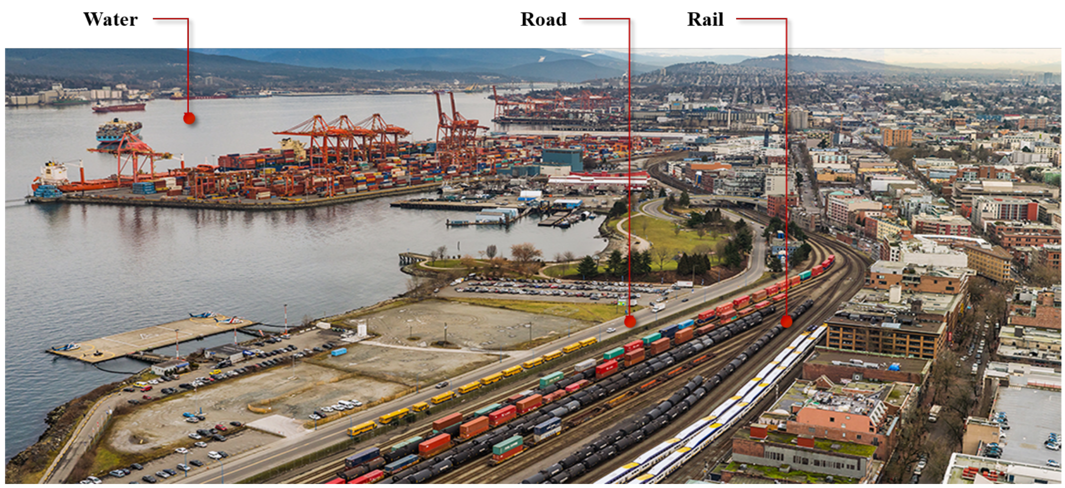


Figure 1.1: Example of an intermodal terminal with three transportation modes of water, road, and rail

Microgrid is one of the technology-based solutions that can be implemented at ports not only to mitigate the existing problems but also to enable a prosperous future for the ports. A microgrid is a relatively small-scale localized energy network that features an effective integration of high penetration level of Distributed Energy Resources (DERs), such as renewable energy resources, energy storage devices, and controllable loads [7]. A microgrid can operate both in island mode (i.e., disconnected from the main utility grid) or in connected mode. The islanding capability of the microgrid enables its performance and power demand satisfaction while the main grid is disrupted. Compared with the traditional centralized operation paradigm of bulk power systems, microgrid offers various advantages such as enhanced power quality, reduced cost, improved resiliency, and a more reliable, continuous, controllable and clean power supply. It is envisioned that microgrids add the missing "piece" which the port authorities and agencies have been searching for a long time to make traditional ports smart. Microgrids can provide the energy required to support the latest technology-intensive and information-centered economy models that the port entities are actively adopting as a part of the port modernization and electrification. The secure, high-quality, and green energy that microgrid can provide opens up opportunities for technology integration, capacity expansion, sustainability enhancement, and business continuity to further improve the port's smartness.

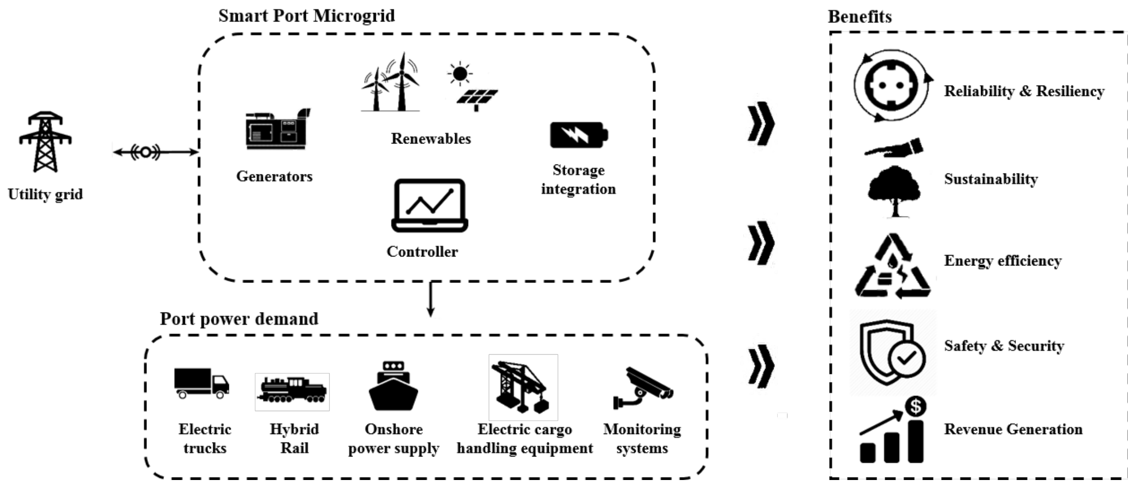


Figure 1.2: Microgrid and the benefits of its implementation at ports

As mentioned before, port activities and development are accompanied by adverse environmental impacts such as air pollution. Approximately 230 million people are directly exposed to the emissions in the top 100 world ports and most air pollutants in ports (CH_4, CO, CO_2 and NO_x) are estimated to quadruple by 2050, which means 70 million tonnes of CO_2 and 1.3 million tonnes of NO_x from shipping emissions in ports by 2050 [8]. These pollutants significantly impact the residents of the local community surrounding ports and the growing concentration of them is associated with increased natural disasters, environmental deterioration, and threats for human health and safety including asthma, cardiovascular disease (Figure 1.3), lung cancer, bronchitis symptoms, premature births, and premature mortality ([9], [1]).

Principal sources of airborne emission at ports are Ocean-going vessels (OGVs), cargo handling equipment (CHE), heavy-duty vehicles (HDVs), and harbor craft, respectively (Figure 1.4). Existing port emission mitigation strategies embrace technical, operational, and economic dimensions. The abatement measures for OGVs are classified into four categories: alternative fuels or power sources, operational measures, technical measures, and structural changes. Zero emission transport vehicles and zero emission cranes are available to reduce CHE emission. Moreover, alternative fuels, speed optimization, idling reduction, and truck platooning are adoptable approaches for HDVs emission reduction.

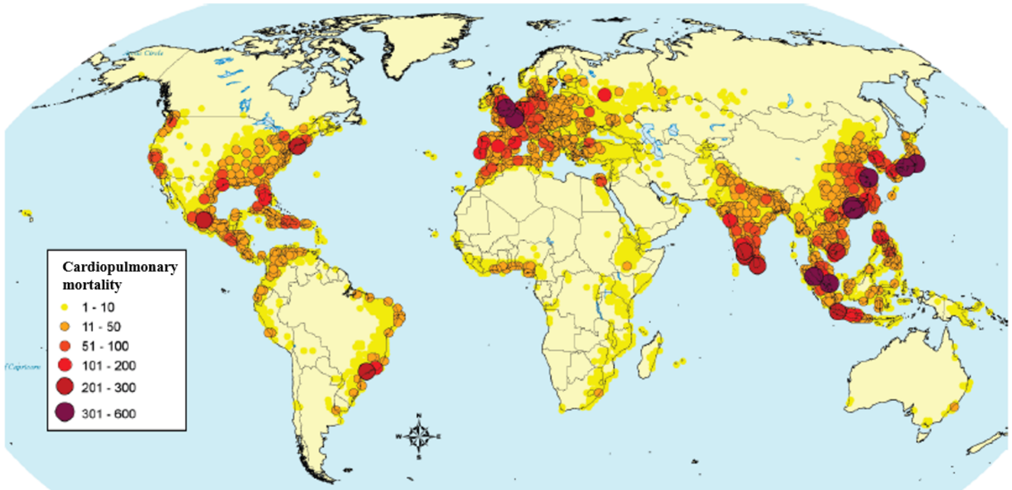


Figure 1.3: Cardiopulmonary mortality attributable to ship $PM_{2.5}$ emissions worldwide (2007) [1]

Despite the existence of various solutions for the sustainable development of the ports, port authorities, port operators, and shipping liners are reluctant to initiate them. This is due to the barriers to implementation in terms of cost, time, and market availability. More importantly, both ports and shipping liners priorities are to increase their own profit; hence, they are not motivated enough to participate in the greening process. To address this issue, the regulations and economic incentives for emission reduction have emerged. In this regard, two types of instruments are available for the policy-makers, traditional mandatory regulations, and market-based policies [10]. The former one is a standard which obliges specific technologies or processes that polluters must adopt to reduce their emission. While regulatory approaches are have been effective, incentive-based policies are growing more attractive to policymakers. This raising interest is due to the flexibility and willingness they give to the polluters as well as the higher effectiveness of the approach.

1.2 Problem Description

With global trade development, ports have faced increasing pressure to optimize their performance in terms of economic, environmental, energy, and functional challenges that impact their

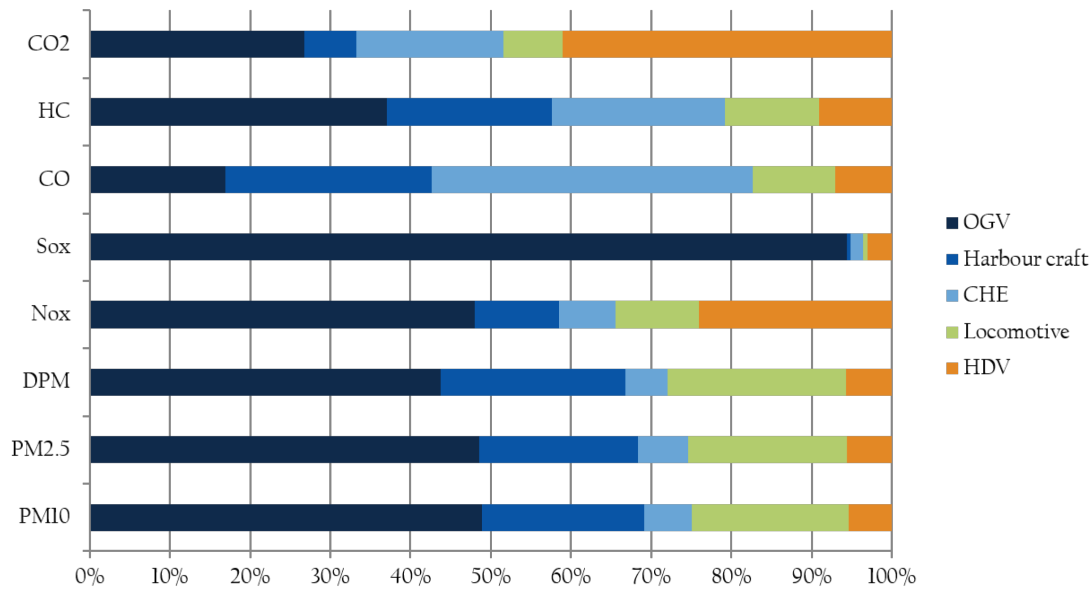


Figure 1.4: Emission Sources in port of Los Angeles (2015) [2]

sustainability. Key elements and associated issues in the ports include operations, environment, energy, safety, and security. These areas and their associated problems are explained in more details in the following:

- **Operations**: Ports receive different types of vessels, including containerships, cruise vessels, tankers, RoRo ships, auto carriers, bulk carriers, and refrigerated vessels (reefers). The main operation of the port is to load and unload these vessels and handle the process of transporting the cargo to warehouses or other destinations. With the increasing demand for port operations, there has been raising issues related to congestion, delays, operating errors, and lack of information sharing in the port.

- **Environment**: Ports can be the source of environmental pollution through land and sea transportation, industrial activities, waste disposal, construction, and expansion activities. The environmental issues caused by the port operations include emissions to air, noise pollution, water pollution and consumption, and waste generation. These environmental issues reduce social welfare and pose a threat to the survival of living creatures; thus, they cause critical challenges for port managers and menace the ports' endurance in the future competitive era.

- **Energy**: The port and its logistics are large consumers of energy. Along with the development of ports, the rise in the demand for maritime transportation, and the increase in industrial activities in ports, the demand for energy as well as costs further increases. Moreover, power related reliability issues and huge impact of the energy disruption on the port activities cause concerns for the port operators and authorities.

- **Safety and Security**: Ports are vulnerable to several safety and security issues, which can potentially cause a loss in terms of benefits, port reputation, and the efficiency of operations. Inherent risks in the port activities associated with safety (e.g., berthing impacts, vessel collisions, and striking while at berth), natural hazards, direct attacks by terrorists, utilization of ports as a conduit for the movement of weapons, armed robbery, cybersecurity issues, unlawful acts, stowaways, drug smuggling are the prominent issues in this area.

These issues may persist if preventive and corrective actions are not planned and performed in a timely manner. To address these problems, smart ports are under development around the world which adopt technology-based solutions as well as better approaches to management and decision-making. Despite the recent emergence of the smart port concept, a unified definition of a smart port and its associated key activity domains have not been well addressed in the literature.

Regarding the solutions for mitigating the existing issues in the ports, there are several studies in the literature each of which has targeted specific areas. Some of the well-studied topics include emissions (e.g., evaluation of emissions from vehicles, emission mitigation strategies: their costs and benefits), carbon footprint case studies, ship mobility emissions (e.g., emissions from maneuvering ships, direct and feeder services), ship design (e.g., energy efficiency and cost effectiveness), fuel consumption, diesel engines, routeing, vessel and truck speed optimization, and scheduling. However, these solutions are each limited to a single area and may not significantly improve the overall port performance. Moreover, microgrid integration into the port power system is very recent, and there are very few studies existing in the literature focusing on port microgrid and its benefits.

Moreover, the port performance improvement sometimes may require huge investments. The costs associated with upgrading and expansion of the infrastructure can often detain and prevent port operators and authorities from initiating sustainability efforts. The regulations and economic incentives are the two common tools of the decision makers to motivate the polluting entities to reduce their emissions. Incentive-based policies are growing more attractive to policymakers because of the flexibility and motivation that they give to the polluters.

1.3 Objectives and Contributions

This proposal addresses the problem of designing smart ports by integrating sustainable infrastructure and economic incentives.

The first contribution aims to propose a smart port definition and its activity domains based on the provided literature and stimulate a path toward smarter ports by providing a formal definition of smart port and its quantitative measure "smart port index" for port authorities. Therefore, we contribute to the literature by following:

- Providing information about the current smart port initiatives around the world and categorizing them into two groups of multipurpose initiatives and targeted initiatives.

- Proposing a definition and activity domains of smart port based on the classified literature: A smart port gathers better-educated individuals, skilled workforce, intelligent infrastructures, and automation to facilitate knowledge development and sharing, optimize the port operations, enhance the port resiliency, lead a sustainable development, and guarantee safe and secure activities. Smart port activity domains are detected to be operations, energy, environment, and safety and security.

- Developing a quantification approach based on the key performance indicators associated with each smart port activity domain and providing a single index for measurement of a smart port performance in its four activity domains.

- Providing a case study of fourteen ports that are selected among the world's busiest ports in terms of numbers of annual TEUs and analyzing how these ports are performing to meet a typical smart port's objectives.

- Analyzing and determining some of the leading factors of the current smartness state of ports by providing a regression analysis focusing on the influence of geographical, economic, political, and energy-related factors on the port smartness.

The second contribution suggests microgrid integration into the port power system to facilitate achieving the goal of becoming smart, sustainable, resilient, and reliable. We are aiming to provide criteria for determining whether for a port entity it is a meaningful decision to integrate the microgrid or not. The contributions of this work include:

- Discussing and proposing a rigorous and logical process to evaluate how the adoption of microgrids can systematically improve a port's performance in its four main activity domains: operations, environment, energy, safety and security. Our work is one of the pioneering research efforts to evaluate and quantify the benefits provided by microgrids to create sustainable value for a smart port.

- Proposing and applying a set of Smart Port Index (SPI) metrics that are based on the KPIs collected in the first contribution to quantitatively evaluate the benefits that microgrids could contribute to port performance. This provides an analytic approach for key stakeholders (regulators, port authorities, industrial partners) to evaluate how a microgrid can help a port meet its performance objectives based on a list of factors.

- Developing a two-stage stochastic mixed-integer programming model to demonstrate how this index can significantly improve the smartness of the port when it is used in the context of microgrid incorporation into port operation and management. The model consists of two stages: 1) an *investment* master problem to determine the optimal installation status of the DERs, and 2) a multi-objective *operation* planning subproblem to decide on the optimal hourly power generation, load shedding, and power flow between the microgrid and the utility grid.

- Considering the inherent operation uncertainties associated with renewable power generation and power outage in the stochastic model.

- Performing case studies paired with realistic data to demonstrate how the utilization of the proposed SPI can improve the operation of the Barbours Cut terminal at the Port of Houston compared with conventional microgrid planning approach that does not consider the domain-specific port features.
- Analyzing the influence of assigning different priorities to the goals in the process of developing and planning the microgrid.
- Studying the investment and planning of onshore power supply (OPS) at port microgrids and analyzing the benefits of OPS integration in improving port sustainability and energy efficiency

The third contribution analyzes the process in which a regulatory authority defines incentive and tax policies to motivate one or more ports in the region to initiate green efforts. This study aims to aid both the regulatory entities (e.g., governments, policy makers) and polluting sectors (e.g., ports, shipping liners, shippers) to achieve their goals. The contributions of this work include:

- Modeling the behavior of the regulatory authority and ports by a multi-objective bilevel program to find the optimal incentive and tax policies for the government in the upper level, and provide the ports in the region with the optimal choice of green solutions in the lower level.
- Developing a novel hybrid economic approach to stimulate sustainable energy activities at maritime ports. To our knowledge, this work is one of the pioneering research efforts that aim to combine the certainty of command-and-control and the flexibility of market-based economic incentives in the unique context of maritime transportation.
- Presenting a multi-objective bilevel programming model to enable the co-operation of different stakeholders involved in the design, ownership, operation, and management of port energy systems based on their points of interest as well as the hierarchy and competition among them.
- Providing numerical results based on actual port data and reveal and offer insights into the effectiveness of taxes, incentives, and the combination of the two on mitigating emissions with the consideration of the satisfaction of port energy demand.

1.4 List of Outcomes

1.4.1 Journal Publications

- Anahita Molavi, Gino Lim, and Bruce Race (2019) "*A Framework for Building a Smart Port and Smart Port Index*," International Journal of Sustainable Transportation.
  DOI: 10.1080/15568318.2019.1610919.

- Anahita Molavi, Jian Shi, Yiwei Wu, and Gino Lim (2020) "*Enabling Smart Ports Through the Integration of Microgrids: A two-stage stochastic programming approach*," Applied Energy 258, 114022.

- Anahita Molavi, Gino Lim, and Jian Shi (2020) "*Stimulating Sustainable Energy at Maritime Ports by Hybrid Economic Incentives: A Bilevel Optimization Approach*," Applied Energy (under revision).

- Anahita Molavi, Jian Shi, and Gino Lim (2020) "*A Decentralized Trilevel Optimization Approach for Promoting Sustainable Energy and Onshore Power Supply at Ports*," to be submitted.

1.4.2 Conference Proceedings

- Anahita Molavi, Gino Lim, and Bruce Race (2019) "*Smart Ports: The Future of Maritime Transportation*," Proceedings of THC-IT-2019 Conference & Exhibition.

- Anahita Molavi, Jian Shi, and Gino Lim (2020), "*Co-Optimization of Onshore Power Supply and Port Microgrid Under Uncertainty*," In 2020 IEEE Transportation Electrification Conference and EXPO, ITEC 2020. IEEE Transportation Electrification Conference (in press).

1.4.3 Posters

- Anahita Molavi, Jian Shi, Yiwei Wu, and Gino Lim, "*Enabling Smart Ports Through the Integration of Microgrids*," THC-IT-2019 Conference & Exhibition, Houston, TX, Aug 2019.

1.4.4 Conference Presentations

- Anahita Molavi, Gino Lim, and Bruce Race, "*A Framework for Building a Smart Port and Smart Port Index*," INFORMS Annual Meeting, Houston, TX, Nov 2016.
- Anahita Molavi, Gino Lim, and Bruce Race, "*Smart Ports: The Future of Maritime Transportation*," THC-IT-2019 Conference & Exhibition, Houston, TX, Aug 2019.
- Anahita Molavi, Jian Shi, Yiwei Wu, and Gino Lim, "*Enabling Smart Ports Through the Integration of Microgrids*," INFORMS Annual Meeting, Seattle, WA, Oct 2019.

1.5 Organization

This dissertation is organized as follows. Chapter 2 is a comprehensive overview of the relevant literature on smart ports, microgrid planning for the ports, and economic incentives for the sustainable development of the ports. Solution domain history including a review on mixed integer programming, two-stage stochastic programs with recourse, Benders decomposition, goal programming, Latin-Hypercube Sampling, scenario reduction, and multilevel optimization is also provided.

In Chapter 3, we present our study on the smart ports and provide a framework for building a smart port and smart port index. Smart port definition and activity domains are identified, and indices are developed based on the existing KPIs in the literature. Case studies are conducted to show how one can use SPI and to assess the performance of some of the busiest ports in the world. The drivers of current smart port states are analyzed by performing a regression analysis to examine the influence of region-specific variables on the port performance.

In Chapter 4, a two-stage stochastic mixed-integer programming model is developed to explain how the use of microgrid at a port can effectively enhance the port's performance in four key activity domains: operations, environment, energy, safety and security under operation uncertainty. The proposed model consists of an investment master problem in the first stage and a multiobjective operation planning subproblem in the second stage. Benders decomposition is implemented for solving the two-stage stochastic model, and Lexicographic Goal Programming is applied to the subproblem to deal with multiple objectives. Case study of Barbours Cut terminal in Port of Houston is provided, and the results are compared with the minimum cost planning approach as well as the situation that microgrid is not installed.

Chapter 5 studies the investment and planning of onshore power supply (OPS) at port microgrids and analyzes and evaluates the benefits of OPS integration in improving port sustainability and energy efficiency. We show how OPS can be installed and planned along with the microgrids at ports to provide clean power to the vessels at berth. A two-stage stochastic mixed-integer programming model is developed to model and investigate the effectiveness of developing OPS for port microgrids under uncertainty associated with renewable energy and islanding operations. The proposed model includes an investment master problem on the first stage and an operation planning subproblem on the second stage. Numerical results illustrate that the integration of OPS along with port microgrid noticeably reduces emissions from the port activities without hindering the economics and competitiveness of the port entity.

In Chapter 6, we analyze the process in which a regulatory authority defines regulations, incentives, and tax policies to motivate one or more ports in the region to initiate energy sustainability and emission-reduction efforts. We model the behaviors of both the regulatory authority and the participating ports in the form of a multi-objective mixed-integer nonlinear bilevel optimization problem to capture the hierarchy of the policy-making process and the existing competitions among the ports. The proposed model finds the optimal incentive and tax policies for the policy-maker in the upper-level and provides the ports in the region with the optimal choice of smart and sustainable energy solutions and service prices in the lower-level. Simulation results show that the proposed approach can effectively reduce the region-wide emission due to port activities while ensuring port entities' welfare, competitiveness, and sustainable growth as regional energy hubs.

Chapter 7 concludes the dissertation with a summary of our contributions and provides the future researches that can be pursued.

Chapter 2

Literature review

In this chapter, first, the problem domains of smart ports, economic incentives for sustainable development, and microgrids and related research work are presented. Afterward, a brief history along with some bibliographical references on methodological backgrounds and solution techniques used in this study are provided.

2.1 Problem Domain Review

This section provides a review of ports research with emphasis on smart ports, microgrid planning for ports, and economic incentives for sustainable development.

2.1.1 Smart Ports

Sporadic efforts have been made for developing a smart port around the world. However, this topic is very recent and has received limited attention from the academic community, and there are few studies in the literature analyzing this phenomenon and addressing the problems associated with it. However, tracking the genealogy of the word "smart" in similar areas assists us in the understanding of why this term has emerged. In the technology setting, smartness refers to the automatic computing principles such as self-configuration, self-protection, self-healing, and self-optimization [11]. In the urban planning field, smart growth emerged during the 1990s as a potent government- and society-driven reaction to exacerbating trends in the loss of open space, air pollution, obliteration of historical places, traffic congestion, and increasing public facilities cost [12]. The term "smart growth" refers to an approach (public or private) to managing development that leads to economic advancement without the congestion and environmental degradation. Smart City maximizes services to the citizens while monitoring and integrating critical infrastructures, planning preventive maintenance actions, optimizing resources, and monitoring security aspects [13]. Governments and public agencies at all levels are embracing the notion of smartness to characterize their new policies aiming for sustainable development, sound economic growth, and better quality of life for the citizens. Being smart involves strategic directions and is associated with achieving policy success [14]. Smart homes, buildings, airports, hospitals, and ports are equipped with mobile terminals, embedded devices, sensors, and actuators [15].

That current smart port initiatives around the world can be categorized into two groups: multipurpose initiatives and targeted initiatives. Smart port multipurpose initiatives include those practices with comprehensive long-term plans and strategies covering various aspects of port activities. These are primarily being conducted by large ports or associations. As a first step, port authorities have detected and evaluated current and possible future problems, and have identified solutions for eliminating or avoiding them. One major common goal is to develop efficient operations and logistics through automation and technology propagation or by modifying strategies and policies ([16]; [17]; [18]). Topics related to environment and energy have formed other pillars of these initiatives such as implementing renewable energy, reducing energy consumption, and improving operations to be environmentally friendly ([16]; [19]; [18]). This category includes MedMaritime SMARTPORT [16], Port of Rotterdam Smart Port [18], Port of Hamburg Smart Port ([19]; [17]), Erasmus Smart Port Rotterdam [20], and Port of Amsterdam Smart Port ([21]; [22]).

Smart port targeted initiatives seek to eliminate specific obstacles in ports. These initiatives are largely focused on special-purpose Information and Communication Technology (ICT) applications and regulation-based approaches in the setting of smart ports. ICT contributes significantly to the trend toward smart ports. Ports can take advantage of ICT for improving knowledge sharing and information analysis to increase operations and energy efficiency as well as environmental sustainability.

The City of Hamburg has adopted the SmartPort Solution by AGT International^{TM} [23]. This solution includes a port-wide Cisco Wi-Fi Real-Time Locating System (RTLS) that detects RFID tags continuously in the port. This technology recognizes and traces barges in real time. SmartPort Platform is another tool that has a distributed architecture and performs data collection of the port sensors, data visualization, and data analysis. This platform facilitates the processing of big data volumes from the sensors that register environmental parameters and dynamic parameters about the vessels [24]. In the private sector, companies such as Kalmar Smart Port and Arelsa Company ([25]; [26]) offer automation solutions for smart ports. As another instance of technology-dependent solutions, ABB organization [27] markets shore to ship power (onshore power supply) and other reliable, green, and efficient electrification solutions.

The Port Authority of Cartagena has adopted the Posidonia SmartPort application to share instant information about vessel situation, movements, operations, traffic history, and forecasts [28]. The Port Authority of Singapore (MPA) has employed mobile technology and wireless connectivity to improve efficiency, communications, and crew satisfaction in the Port of Singapore [29].

Malaysian and Singaporean ports have implemented Integrated Port Management System (IPMS) which incorporates multiple ports on a single platform ([29]; [30]). The Kenya Ports Authority (KPA) automated processes such as time management and payroll functions. Moreover, the KPA runs a security management system that automates all entry and exit points for vehicles and passengers and facilitates yard management with sensors to gain full transparency on the location and movement of containers [31]. In addition to adopting existing technologies, the Port of Singapore and the Port of Rotterdam have held hackathons separately to discuss possible future projects and existing ideas in the area of smart ports ([32]; [20]).

In the context of smart ports, regulation-based approaches from the United Nations Conference on Trade and Development (UNCTAD), International Maritime Organization (IMO), and European Union (EU) exist [6]. These legislations aim to improve port sustainability, motivate the implementation of new technologies, and provide standards for assessing port performance. Similarly, the U.S. Department of Homeland Security introduced the Smart Port Security Act, which enhances risk-based security measures to prevent threats from reaching the ports [33].

2.1.2 Integration of Microgrid and Onshore Power Supply into the Port Power System

Electricity has become the dominant medium to integrate, store, and transport energy, and thus is playing a critical role in the global energy supply chain. With large numbers of operations demanding significant power, there are many existing and ongoing efforts around the world to create integrated energy, sustainability, and business solutions that incorporate the concept of microgrids.

In the United States, Port of Los Angeles (POLA) has recently invested $27 million in microgrid development and distributed clean energy resource technologies. As a demonstration project, a microgrid that incorporates a 1 MW solar PV array, an onshore 2.6 MWh battery storage system, and the associated electrical infrastructure upgrade has been completed in the Omni Terminal and expected to serve as a model for the modernization of 26 other marine cargo terminals at POLA. Port of Long Beach (POLB) has been evaluating microgrid development to support the port's Energy Island Initiative. The evaluation concluded that the development of a microgrid would effectively assist POLB's transition toward renewable energy and serve the port's needs for energy reliability, power quality, and economic stability ([34], [35]). In 2018, Port of San Diego was awarded $5 million grant from California Energy Commission for the installation of a renewable-energy-based microgrid at the Tenth Avenue Marine Terminal [36]. The project includes the installation of solar PV panels, battery energy storage, a microgrid controller, and other infrastructure improvements to provide back-up power to port-operated facilities and support military deployment activities.

In Europe, the city of Rotterdam has been partnering with General Electric to transform the Port of Rotterdam into a virtual power plant (VPP) that consisting of a coordinated cluster of microgrids. Built on thermal and renewable power production, the Port is expected to function as a smart energy grid with reduced emissions, enhanced demand-side management, and increased energy efficiency [37]. Microgrids can be especially helpful where shore-to-ship power transfer is offered to reduce the emissions and noise levels of vessels docked in port. As a representative example, Port of Gothenburg has the first 50/60 Hz shore connection in Sweden and shore-side power supply to a vast number of cargo vessels while at berth featuring fully automated power transfer. Port of Dalian in China, Port of Fincantieri in Italy, Port of Ystad in Sweden, and Port of Moin at Costa Rica, among others, are instances of a broader effort to electrify the processes, services, and equipment [38].

As G. Parise et al. state [39], the energy management at ports as well as optimization and control of the energy flows can be a great business opportunity for port authorities. This can also be beneficiary for different stakeholders such as power utility companies and the nearby urban areas. Their work suggests that ports should arrange their microgrids which are adequate even to power the ships from shore in addition to the port demand. MG installation is believed to be one of the best approaches to supplying the power associated with onshore-power-supply, all-electric-ships, and shipboard power systems ([40], [41], [42]).

Along with energy management, microgrid facilitates reducing emissions such as greenhouse gasses. The proliferating number of global trade in recent years, 90% of which are being transferred by maritime transportation, highlight the need for seeking clean power sources such as microgrids [43]. A study by A. Misra discusses the ways to reduce greenhouse gas emissions inside the port by efficiently incorporating renewable energy sources using microgrids [44].

Combined with a microgrid, vessels can be hooked up to an onshore power supply (OPS) which is an alternative to the traditional power supply and a solution to the ports' emission problem. OPS, or cold-ironing, provides power to vessels at the berth through shore-to-ship power cables in which auxiliary engines on-board can be turned off. This power supply ensures that the ship's operations can be performed without any interruption, and air emissions from diesel fuels caused by berthing activities will be reduced noticeably [45]. Currently, many industrial ports around the globe, including Port of Antwerp, Port of Gothenburg, POLA, and Port of Seattle, are testing and moving toward integrating OPS [45] technologies into their terminal electricity distribution systems. In fact, Onshore power supply (OPS) is one of the strategies recommended by the World Port Climate Initiative for reducing the environmental issues caused by vessels berthing at the ports. Despite the evident benefits, currently, only limited ports and vessels are equipped to be capable of utilizing OPS due to the fact that implementing OPS requires a comprehensive study on the port conditions, existing regulations, feasibility of implementation, cost-effectiveness, and optimal quantities and locations for installations.

2.1.3 Economic Incentives and Sustainable Development of Ports

In the context of emission abatement technologies and approaches at ports, research in various areas exists in the literature. Vessel speed optimization, berth allocation, crane scheduling, and shipping routing and scheduling are the major subjects of these studies ([46], [47], [48]).

As for the economic regulations, Tseng et al. have developed an empirical bottom-up activity-based model for estimating the air pollution cost from ships at berth, and investigated the necessity of pollution tax through a survey [49]. The results of their study show that pollution is measurable, and the pollution tax is theoretically necessary and effective. Moreover, their interview with the port operators and government officials reveals that the port operators are not willing to follow mandatory rules, and they need the flexibility to lower their emission. Government officials also highlighted the importance of a practical approach for determining a policy which motivates ports to reduce their emission. Capturing the uncertainty in the nature of emission regulation policies has been the subject of several studies. La Torre et al. [50] have discussed the application of the environmental policy on air emission mitigation in a stochastic framework with finite horizon and sustainability concern. Their work considers economic and pollution costs at the same time, which allows the decision makers to obtain a satisfactory policy in both terms. Structural uncertainty in pollution control and its effect on the optimal stringency of environmental regulation is also the subject of a study by Carson et al. [51]. As another instance, a two-stage inexact-stochastic programming (TISP) method has been developed by Chen et al. for planning carbon dioxide (CO_2) emission trading under uncertainty [52].

When incentive-based policies are the subject of studies, a mathematical model should consider both the decisions of the polluting industry and the regulatory entity. As such, a market-based policy on pollution control in a region with multiple ports is proposed in a study by Homsombat et al. [53]. The paper investigates the behavior of port customers and ports themselves in facing a specific incentive or tax policy by a one-shot Cournot game. The possibility of having multiple ports in the region and their competition is another factor to consider, which enhances the validity of the results. Sheng et al. [54] have developed a model to investigate the economic and environmental effects of a unilateral maritime emission regulation versus a uniform maritime emission regulation in the presence of multiple ports. The results of this work indicate that unilateral regulation may lead to an increase in total emissions, whereas a uniform regulation always reduces total emissions. Hence, policies should create a balance between emission reduction and fair competition.

Bi-level models can describe similar situations as game theoretic approaches. As such, a situation where the government aims to minimize the total CO_2 emissions by using carbon tax and subsidies and the consumers want to minimize their costs by choosing the optimal combination of energy [55]. Also, a bilevel optimization for designing effective incentive policies that motivate investment in renewable energy by imposing a carbon tax and subsidies has been developed in a work by Zhou et al. [56]. As another instance, through bi-level programming and for a market with multiple players, Almutairi et al. [57] designed a carbon tax scheme based on the production emission factor.

To provide the polluting industries with optimal policies of emission reduction in response to the existing environmental regulations, some studies analyze the choice of green technologies. In this regard, the impacts of emissions tax and emissions cap-and-trade regulation on a firm's technology choice and capacity decisions are the subject of Drake et al. [58]. C. Fisher and R. Newell have also assessed different policies for reducing carbon dioxide emissions and promoting innovation and diffusion of renewable energy [59].

2.2 Solution Domain History

This section briefly reviews the history of mathematical tools and techniques that are used in this study and provides the relevant references for the readers. These techniques include mixed integer programming, two-stage stochastic programs with recourse, Benders Decomposition, goal programming, Latin Hypercube Sampling (LHS), scenario reduction, and multilevel optimization.

2.2.1 Mixed Integer Programming

A Mixed-Integer Programming (MIP) problem is an optimization model in which some of the decision variables are real-valued and some are integer-valued. MIP theory and practice has been the subject of several studies during the last 50 years ([60], [61], [62], [63], [64], [65]). There are also successful and effective solution approaches existing in the literature which are mainly based on branch-and-bound techniques [66]. Solvers such as CPLEX [67] and Gurobi [68] have been of significant help in solving MIP problems.

2.2.2 Two Stage Stochastic Programs with Recourse

One class of optimization models with uncertainty is two-stage stochastic programs with recourse. In this type of problems, some parameters are subject to uncertainty and their exact values cannot be determined at the time of planning. Hence, the decision maker decides on some action in the first stage, then a random event occurs and affects the outcome of the first-stage decision. Second-stage decisions are called recourse decisions which are made to compensates for any adverse effect that first-stage decisions have caused. The earliest studies in this area include the works by Dantzig [69] and Beale [70].

2.2.3 Benders Decomposition

This study has taken advantage of implementing Benders Decomposition technique for decomposing the stochastic models. Benders Decomposition algorithm was developed by J. F. Benders [71] for solving large-scale, mixed-integer programming problems. This decomposition method has been applied to various optimization problems [72].

2.2.4 Goal Programming

Goal programming is a branch of multi-objective optimization that can handle multiple, normally conflicting objective terms. Each of these terms is associated with a goal or target value and unwanted deviations from this set of target values should be minimized. Thus, the objective function can be a vector or a weighted sum based on the problem specifications [73]. This study uses the preemptive goal programming [74] approach to solving the optimization models with multi-objectives and known target values.

2.2.5 Latin Hypercube Sampling (LHS)

A latin square is a square grid that contains sample positions and there is only one sample in each row and each column. A Latin hypercube generalizes this notion to random dimensions. Latin

Hypercube Sampling (LHS) was described by McKay in 1979 [75] and it is a statistical sampling method for generating a near-random sample of parameter values from a multidimensional distribution. This sampling method makes sampling point distribution close to the determined probability density function and it is more accurate than random sampling.

2.2.6 Scenario Reduction

To solve the two-stage stochastic problem numerically, one often needs to assume that the random vector has a finite number of possible realizations, called scenarios [76]. Considering all of the scenarios for solving the model leads to a huge computational complexity and requires great extent of time and memory [77]. Hence, it is very common in the literature to approximate the problem by a reduced number of scenarios [78]. Efficient scenario reduction algorithms exist in the literature which facilitate obtaining a set of scenarios which are a good representation of the original set [79]. GAMS also offers a scenario reduction tool, called SCENRED, which is capable of offering reduced scenarios and probabilities based on the original scenario tree and the required accuracy level or the size of the reduced scenarios [80].

2.2.7 Multilevel Optimization

In multilevel systems, the decision maker at one of the levels may be able to influence the behavior of the decision maker at another level, but this is limited to influence and not complete control. Each level may have its own decision variables, constraints, and objectives. The common features of multilevel systems are: 1) interactive decision-making units within a predominantly hierarchical structure, 2) executing the subordinate level policies after the superordinate level, 3) maximizing each unit benefit separately considering each are affected by the actions of other units, and 4) the actions of units influences the objective and feasible strategy set of the others. These problems can be viewed as an l-person, nonzero-sum game with perfect information, at least for the higher level players, where the order of play is predetermined and the players' strategy sets are not disjoint [81]. Bilevel programming is a special case of multilevel programming in which there are two levels. Multilevel programming was first introduced during the 1970s by Chandler and Norton [82]. The study on the theory and applications of multilevel systems and more specifically, the bilevel programming, have been the subject of many studies since then ([83], [84], [85], [86], [87], [88], [89])

Chapter 3

A Framework for Building a Smart Port and Smart Port Index

3.1 Introduction

Ports are regional multimodal intersections of global supply chains. They function in the context of complex infrastructure, business transactions, and regulations. With the global economy demanding maritime transportation, ports have faced increasing pressure to optimize their performance in terms of economic, environmental, energy and functional challenges that impact their sustainability.

Key elements and associated issues include operations (e.g., congestion, delays, operating errors, and lack of information sharing [90]), environment (e.g., air, water and noise pollution, waste disposal, construction and expansion activities [91]), energy (e.g., increasing energy consumption, increasing energy costs, and energy disruption impacts on the port activities [92, 93]), safety (e.g., berthing impacts, vessel collisions, and striking while at berth [94, 95]), and security (e.g., armed robbery, cyber security issues, unlawful acts, stowaways, drug smuggling, use of ports as conduit for moving weapons and terrorist attacks [96, 97, 98]). These issues may persist if preventive and corrective actions are not planned and performed in a timely manner. In response to the existing problems, ports are adopting technology-based solutions, as well as new approaches to port operations planning and management. Implementation of such solutions to mitigate recent problems is known to be switching to smart ports.

Our comprehensive literature review reveals two different perspectives of a smart port. One perspective is that the smartness of a port relates more to the ideology rather than technologies and physical infrastructures. In other words, policy decisions and the smart use of resources are more important than the implementation of technologies. Another view of smartness is related to the utilization of recent technologies in order to improve the port performance or provide solutions for energy and environmental issues [99].

Literature review reveals that current smart port initiatives around the world can be categorized into two groups: multipurpose initiatives and targeted initiatives.

Smart Port Multipurpose Initiatives

This category includes those practices with comprehensive long-term plans and strategies covering various aspects of port activities. These are primarily being conducted by large ports or associations. As a first step, port authorities have detected and evaluated current and possible future problems, and have identified solutions for eliminating or avoiding them. One major common goal is to develop efficient operations and logistics through automation and technology propagation or by modifying strategies and policies [16, 17, 18]. Topics related to environment and energy have formed other pillars of these initiatives such as implementing renewable energy, reducing energy consumption, and improving operations to be environmentally friendly [16, 19, 18]. This category includes MedMaritime SMART-PORT [16], Port of Rotterdam Smart Port [18], Port of Hamburg Smart Port [19, 17], Erasmus Smart Port Rotterdam [20], and Port of Amsterdam Smart Port [21, 22].

Smart Port Targeted Initiatives

Smart port targeted initiatives seek to eliminate specific obstacles in ports. These initiatives are largely focused on special-purpose Information and Communication Technology (ICT) applications and regulation-based approaches in the setting of smart ports. ICT contributes significantly to the trend toward smart ports. Ports can take advantage of ICT for improving knowledge sharing and information analysis to increase operations and energy efficiency as well as environmental sustainability.

The City of Hamburg has adopted the SmartPort Solution by AGT International™ [23]. This solution includes a port-wide Cisco Wi-Fi real-time locating system (RTLS) which detects RFID tags continuously in the port. This technology recognizes and traces barges in real time. SmartPort Platform is another tool which has a distributed architecture and performs data collection of the port sensors, data visualization, and data analysis. This platform facilitates the processing of big data volumes from the sensors that register environmental parameters and dynamic parameters about the vessels [24]. In the private sector, companies such as Kalmar Smart Port and Arelsa Company [25, 26] offer automation solutions for smart ports. As another instance of technology-dependent solutions, ABB organization [27] markets shore to ship power (onshore power supply) and other reliable, green, and efficient electrification solutions.

The Port Authority of Cartagena has adopted the Posidonia SmartPort application to share instant information about vessel situation, movements, operations, traffic history, and forecasts [28]. The Port Authority of Singapore (MPA) has employed mobile technology and wireless connectivity to improve efficiency, communications, and crew satisfaction in the Port of Singapore [29].

Malaysian and Singaporean ports have implemented Integrated Port Management System (IPMS) which incorporates multiple ports on a single platform [29, 30]. The Kenya Ports Authority (KPA) has automated processes such as time management and payroll functions. Moreover, the KPA runs a security management system that automates all entry and exit points for vehicles and passengers and facilitates yard management with sensors to gain full transparency on the location and movement of containers [31]. In addition to adopting existing technologies, the Port of Singapore and the Port of Rotterdam have held hackathons separately to discuss possible future projects and existing ideas in the area of smart ports [32, 20].

In the context of smart ports, there exist regulation-based approaches from the United Nations Conference on Trade and Development (UNCTAD), International Maritime Organization (IMO), and European Union (EU) [6]. These legislations aim to improve port sustainability, motivate the implementation of new technologies, and provide standards for assessing port performance. Similarly, the U.S. Department of Homeland Security introduced the Smart Port Security Act, which enhances risk-based security measures to prevent threats from reaching the ports [33]. Table A.1 shows the overview of smart port practices grouped into two categories of multipurpose and targeted initiatives (see Appendix A).

Despite the recent emergence of the smart port concept, a unified definition of a smart port and its associated key activity domains have not been well addressed in the literature. Therefore, this paper aims to propose a smart port definition and its activity domains based on the provided literature, and stimulate a path toward smarter ports by providing a formal definition of smart port and its quantitative measure “Smart Port Index" for port authorities. Therefore, this paper addresses three research questions:

1. What are a smart port and its activity domains?
2. How are ports performing to meet a typical smart port’s objectives?
3. What are the leading factors of the current smartness state of ports?

The remainder of this paper is organized as follows. The next section defines a smart port based on the classified literature and identifies its activity domains. Section 3 proposes a collection of KPIs for ports’ smartness assessment, develops a smart port index (i.e., SPI), and evaluates major international ports with regard to the definition of a smart port. Note that there were limitations on data availability and we experienced that not all ports publish the required data for calculating all KPIs being discussed in this paper. Hence, it was necessary for us to modify the index measurement approach to deal with this limitation for the numerical experiments. However, this should not affect the development of the SPI index. Section 4 investigates the effect of region-specific variables on the ports’ performances by analyzing and decomposing SPI, identifies weaknesses and strengths of each port, and suggests possible solutions to overcome deficiencies they may have. Finally, Section 5 concludes this paper and provides possible future research directions.

3.2 Smart Port: Definition and Activity Domains

3.2.1 Smart Port Definition

Sporadic efforts have been made for developing a smart port. However, an internationally accepted and standard definition for the word “smart" does not exist in the context of ports and maritime industry. Tracking the genealogy of the word “smart" in similar areas assists us in the understanding of why this term has emerged. In the technology setting, smartness refers to the automatic computing principles such as self-configuration, self-protection, self-healing, and self-optimization [11].

In the urban planning field, smart growth emerged during the 1990s as a potent government- and society-driven reaction to exacerbating trends in the loss of open space, air pollution, obliteration of historic places, traffic congestion, and increasing public facilities cost [12]. The term “smart growth" refers to an approach (public or private) to managing development that leads to economic advancement without the congestion and environmental degradation. Smart City maximizes services to citizens while monitoring and integrating critical infrastructures, planning preventive maintenance actions, optimizing resources, and monitoring security aspects [13]. Governments and public agencies at all levels are embracing the notion of smartness to characterize their new policies aiming for sustainable development, sound economic growth, and better quality of life for citizens [100]. Being smart involves strategic directions and is associated with achieving policy success [14]. Smart homes, buildings, airports, hospitals, and ports are equipped with mobile terminals, embedded devices, sensors, and actuators [15].

Additionally, comparing the application of potential alternatives to the word “smart" clarifies that it is the right choice to thoroughly describe the concept. Borrowing the word choice philosophy from the Smart City field [12], we can say that the digital port describes a connected port that combines broadband communications infrastructure, flexible and service-oriented computing infrastructure, and innovative services to meet demands. An intelligent port has all the infrastructure and info-structure of information technology and the most recent technologies in telecommunications, electronic, and mechanic. A knowledge port is designed to encourage the nurturing of knowledge. A humane port has multiple opportunities to utilize its human potential and lead creative processes.

However, the port that we have in mind entails all the above aspects as well as the traditional port services and specifications (Figure 3.1). A smart port gathers better-educated individuals, skilled workforces, intelligent infrastructures, and automation to facilitate knowledge development and sharing, optimize the port operations, enhance the port resiliency, lead a sustainable development, and guarantee safe and secure activities. It is sensible that the term “smart port" has prevailed among the public and private sectors to describe the trend. In what follows, we present the activity domains

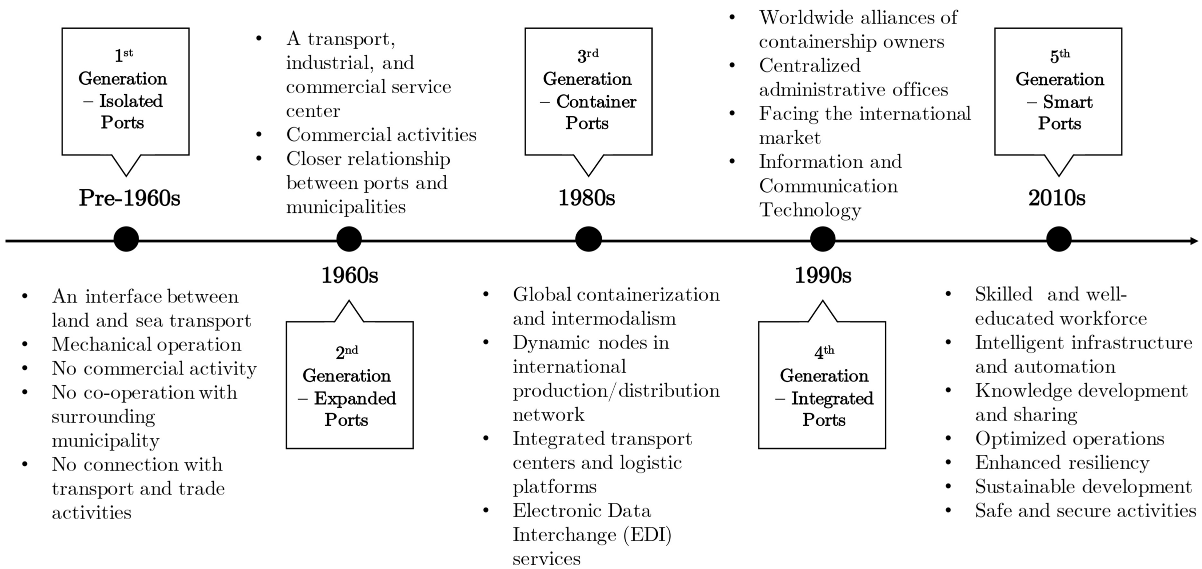


Figure 3.1: Ports development throughout the history [3, 4, 5, 6]

of a smart port that we have identified by classifying the smart port initiatives (Table 3.1). These domains and sub-domains categorize and include different smart port initiatives covered so far and the associated smart port initiative is referenced in the right column.

3.2.2 Smart Port Activity Domains

According to Table 3.1, a smart port consists of four main activity domains: operations, environment, energy, and safety and security. One can assess the port performance in those domains by studying measurable elements which we call “sub-domains" of a smart port and we explain them in more detail.

3.2.2.1 Operations

Ports receive different types of vessels including containerships, cruise vessels, tankers, RoRo ships, auto carriers, bulk carriers, and refrigerated vessels (reefers). The main operation of the port is to load and unload these vessels and handle the process of transporting the cargo to warehouses or other destinations. A smart port utilizes technologies along with adopting innovative

Table 3.1: Classification of a smart port activity domains and sub-domains

Domains	Sub-domains	Description	References
Operations	Productivity	The extent to which the port operations are carried out efficiently within the limits of time, budget, space, and available facilities	[16], [17], [18], [21]
	Automation	Automation is the use of various control systems (set of devices that manages the behavior of other devices or systems) for operating equipment with minimal or reduced human intervention.	[16], [17], [25], [31]
	Intelligent infrastructure	Intelligent infrastructure means the use of technologies, both hardware and software, in the port with the aim to increase efficiency and sustainability.	[16], [17], [18], [26], [28], [29], [6], [24]
Environment	Environmental management systems	Environmental management systems (EMS) are means to help organizations to improve their environmental performance. This aim is achieved through observing and controlling port operations with regard to their environmental impacts.	[16], [18]
	Emissions and pollutions control	Port activities and shipping industry can cause three major types of pollution: emissions to air, noise pollution, and water pollution.	[16], [19], [18], [6]
	Waste management	Ports receive a noticeable amount of waste, sources of which are port activities and vessels.	[16], [19], [18]
	Water management	Water is a vital resource for both human and other species health, so monitoring and controlling the water quality should be part of port plans and strategies.	[16], [19], [18]
Energy	Efficient energy consumption	Several factors influence the energy consumption of a port. These elements could be divided into two categories, direct and indirect energy users. For both groups, saving possibilities should be identified.	[16], [19], [18]
	Producing and use of renewables	Renewable energy is replenishable energy that is generated from natural processes. There are significant possibilities of renewable energy implementation in the ports. This assists in partially or totally covering the port energy demand and significantly reduces pollutions.	[16], [19], [18], [6]
	Energy management	Ports should identify energy management strategies and activities to make efficient use of the available energy.	[16], [19], [18]
Safety and Security	Safety management systems	Safety Management System (SMS) is a comprehensive business management system designed to administer safety principles in the workplace.	[16], [6]
	Security management systems	A security management system identifies potential threats to the port and establishes, implements, monitors, reviews, and maintains all appropriate actions to provide assurance for the effective handling of security risks.	[16], [6], [33]
	Integrated monitoring and optimization systems	Establishing an integrated monitoring and optimization system based on the most recent software and hardware facilitates achieving enhanced security and safety in the port area.	[31]

Table 3.2: Operations: smart port activity sub-domains

Smart Operations		
Productivity	**Automation**	**Intelligent infrastructure**
Berth productivity	Automated stack	Integrated information systems and software
Infrastructure productivity	Automated path	Hardware
Land productivity	Automated rail	
Size and use of maximum capacity	Automated lift	
Lines calling at the port	Automated trucks	
Capacity for receiving large vessels	Automated quay	
Level of Intermodality		

and efficient management models to increase the productivity of port operations and minimize associated costs. Sub-domains of smart port operations include productivity, automation, and intelligent infrastructure (Table 3.2).

Productivity

The global containership fleet capacity will increase by 1685187 TEUs or 8% by 2019, which as a high growth rate clarifies the vitality of improving port productivity which affects country's productivity to a large extent [101]. The productivity of a port operation could be assessed through measuring productivity in seven areas: berth productivity, infrastructure productivity, land productivity, capacity for receiving large vessels, size and use of maximum capacity, the level of intermodality, and lines calling at the port [16].

Automation

Automatized machinery can replace the human workforce in ports and reduce existing human errors, safety issues, port congestions, and turnaround time as well as increasing operations efficiency [16].

Intelligent Infrastructure

Intelligent infrastructure (both hardware and software) in ports can increase efficiency and sustainability by real-time data collection, processing, and sharing. Information regarding traffic flow of both vessels and hinterland transportation vehicles, closure times of movable bridges and other infrastructure information, the situation at the container terminals and other major operations (e.g., empty container depots), and parking facilities should be available to port users [17]. The fast and easy flow of this information facilitates wise and well-informed decision making by port authorities and port customers. This ultimately brings increased productivity, fewer costs, high market competition ability for the port, less emission, energy efficiency, and green logistics. With reference to the current smart port's best practices, implemented intelligent infrastructures in the ports are: sensors, GPS/DGPS, RFID/OCR/LPR, GNSS, DGNSS, TOS, Bluetooth, WLAN, mobile devices, the Cloud, port community systems, port monitor system, port road management system, intelligent railway, smart maintenance, vessel traffic management, parking space management, and gate management.

3.2.2.2 Environment

Ports can be the source of environmental pollution through land and sea transportation and industrial activities. For the purpose of this research, we focus on the following environmental impacts of port activities: emissions to air, noise pollution, water pollution and consumption, and waste generation. These environmental issues reduce social welfare and pose a threat to the survival of living creatures; thus, they cause critical challenges for port managers and menace the ports' endurance in the future competitive era. Smart ports seek solutions to existing environmental problems. We can evaluate the port efficiency in this domain by investigating the port Environmental Management Systems (EMS), pollution reduction activities, and water & waste management.

Environmental Management Systems

Environmental management systems (EMS) offer a framework for evaluating, monitoring, and reducing port environmental impact. The International Organization for Standardization (ISO) has developed the most commonly used framework for an EMS, the ISO 14001 standard. According to ISO 14001, the five main stages of an EMS are as follows: commitment and policy, planning, implementation, evaluation, and review [102]. Two well-known EMS examples include EU Eco-Management and Audit Scheme (EMAS) and Environmental Review System (PERS). EMAS was developed by the European Commission as a means for every organization and organization type to evaluate, report, and improve their environmental performance [103]. PERS is a port-specific environmental management standard developed by EcoPorts. PERS incorporates the main requirements of well-known environmental management standards (e.g., ISO 14001) as well as the specificities of ports [104].

Air Emission Control

The main air pollutants from port activities are CO_2, SO_2, NO_x, Particulate Matter ($PM_{2.5}$ and PM_{10}), HC, CO, and VOC. Air pollution damages the natural environment and can cause harm to human health and other living species [105]. Shipping-related particulate matter (PM) is one of the most dangerous air pollutants and was responsible for approximately 60,000 cardiopulmonary and lung cancer deaths in 2007 [106]. In addition, increasing amounts of greenhouse gases can lead to climate change, ozone layer disruption, and more acid rain [107]. There exist many solutions to decrease emissions such as implementing alternative fuels and zero emission technologies for vessels and land transportation means in ports.

Noise Pollution Reduction

Noise pollution in ports is generated from ferries, ships, industrial activities, shipyard activities, and auxiliary services. This noise pollution can negatively impact the natural eco-system and the urban population [108]. Hence, effective actions should be designed and performed for evaluating, monitoring, and reducing noise pollution at ports.

Waste Management

Ports receive a noticeable amount of waste, sources of which are port activities and vessels. Categorization of ship-generated waste has been established by IMO in the MARPOL 73/78 Convention. According to this convention, six major types of wastes are produced by the vessels: oily waste, bulk chemical waste, noxious substances, packaged form, sewage, and garbage. The same categories can be considered for grouping the port-generated waste [109]. Each of the mentioned types of waste can have environmentally harmful effects if action plans are not devised for handling, recycling, reception, and reducing them to standard amounts.

Water Management

Wastewater from port activities is one of the major environmental concerns since seaports are often situated near residential communities or environmentally sensitive locations. High organic concentration in wastewater assists the growth of different types of bacteria. Wastewater assessment and reduction methods should be implemented in order to reduce the amount of pollutants in the water. In addition to wastewater handling, another issue is the high water consumption of port activities, such as the cooling process. This water is either drawn directly by the port companies themselves (from surface, ground or rain water) or supplied by the water companies. Limited sources of water and rising costs have led to the idea of reducing water consumption.

3.2.2.3 Energy

The port and its logistics are large consumers of energy. Along with the development of ports, the rise in the demand for maritime transportation, and the increase in industrial activities in ports, the demand for energy further increases. Taking into account the limitation of energy sources and port budget, smart port considers approaches to decrease energy consumption. It also suggests the use of renewable energies to both reduce emissions and become independent in terms of energy sources [18]. The sub-domains consists of the use and production of renewable energy, efficient energy consumption, and adopting Energy Management Systems (Table 3.3).

Efficient Energy Consumption

Energy consumers in ports can be divided into two categories: direct and indirect energy consumers. Direct consumers of energy include the lighting system of the port terminal area, offices and other facilities, the office buildings, and the facilities of the garage. Indirect consumers are those with more seasonal consumption patterns. In other words, they depend on the volume of port activities. Indirect consumers include cranes, the internal fleet of the port, and the reefers [16]. Improving the processes and equipment to require less energy and avoid energy loss leads to more efficient energy consumption and lower costs.

Table 3.3: Energy: smart port activity sub-domains

Smart Energy		
Efficient energy consumption	**Use of renewables**	**Energy management**
Energy consumption by containers	Wind energy	Energy management systems
Energy consumption by fleet	Solar power	Monitoring and optimization of energy consumption
Energy consumption by lighting	Biomass energy	
Energy consumption by terminal equipment for movement of containers	Wave and tidal energy	
Energy consumption by offices and companies	Efficient use of solar and electric transportation	

Production and Use of Renewables

Possibilities of implementation of renewable energies are huge in the ports. This assists covering partially or totally the port energy demand. Sources of renewable energy that can be developed in ports are wind technology (off-shore or installed in the terminal area for electric cranes and forklifts), small wind (incorporated in buildings to satisfy the energy demand of offices, garage facilities, and electric vehicles), photovoltaic technology (incorporated in buildings to satisfy the energy demand of offices, garage facilities, and electric vehicles), biodiesel (to provide fuel to internal fleet), and marine technologies (wave and tidal energy conversion to electricity for electric cranes and forklifts) [16].

Energy Management

Energy management systems provide ports with a systematic approach to achieve continuous improvement in energy performance. In this regard, ISO 50001, an international standard for energy management systems, specifies the requirements for designing, applying, maintaining, and enhancing an energy management system. Implementation of ISO 50001, can result in energy performance improvement and energy costs reduction [110]. In addition to energy management systems, ports can optimize energy consumption by continuous monitoring and controlling energy consumption of different activities. An integrated information processing and visualization system in the port assists with reaching this goal.

3.2.2.4 Safety and Security

Ports are vulnerable to several safety and security issues, which can potentially cause a loss in terms of benefits, port reputation, and the efficiency of operations [111]. Direct attacks by terrorists, utilization of ports as a conduit for the movement of weapons [112], natural hazards, and inherent risks in the port activities associated with safety and security are the prominent issues in this area. For example, ports can be exposed to both high−frequency low−severity events (occupational risk) and low−frequency high−severity events (major accident risk) [113, 114, 115]. Smart port uses solutions such as regulations, standards, employee training, periodic control of facilities, risk assessment, proper designs, and monitoring systems to detect any security issue, increase port preparedness, and improve resilience. Overall port performance in this sense is measurable through exploring port safety management systems, security management systems, and integrated monitoring and optimization systems [116, 117, 118].

Safety Management Systems

Safety Management System (SMS) is a systematic and comprehensive process for managing safety risks and is composed of policy, organizing, designing, applying, assessment, and improvement. The system also contains manuals, training, and standards. SMS is applicable to port activities and vessel operations. As another approach to ensure safety at ports, IMO has developed the International Safety Management Code (ISM). In addition to this code, IMO requires all international passenger ships, oil tankers, chemical tankers, gas carriers, bulk carriers, and cargo ships of 500 gross tons or more to implement a SMS.

Security Management Systems

Security management systems identify potential threats to the port and establish, implement, monitor, review, and maintain appropriate actions to effectively handle security risks. Implementation of a security management system will ensure resilience in the face of danger and optimization in terms of cost and loss. Ports need to identify both their assets and possible external and internal threats, perform risk analysis and risk management, and increase the preparedness and awareness of employees. In the meanwhile, steady monitoring and policy evaluation is required to have an up-to-date security management system. International Ship and Port Facility Security Code (ISPS) is introduced by IMO for enhancing security at the ports.

Integrated Monitoring and Optimization Systems

Establishing an integrated monitoring and optimization system based on the most recent software and hardware enhances security and safety in the port area. This includes mainly connecting hardware such as cameras, wireless technology, sensors, RFID tags, and software for data gathering, visualization, analysis, and optimization. Storing the data and analyzing it brings several benefits: real-time information sharing among different port sectors, identification of preventive actions, increased preparedness, effective decision making in the face of unpredicted events, and hence, the resiliency of the port operations.

3.3 Smart Port Index (SPI)

In this section, we introduce a methodology to assess the smartness of a port and develop a rubric as a single index value to capture the port smartness. First, we reviewed the existing Key Performance Indicators (KPIs) in the literature for evaluating the port performance. Four indices were found to be important for measuring smart port performance in its activity domains: operations, energy, environment, and safety and security. Thus, our proposed SPI is a convex combination of these four indices. The SPI can facilitate early detection of deficiencies in any of the four measurement areas to make correctional actions, or help expedite the improvement of port performance. Furthermore, ports can use the SPI to evaluate themselves and know where they stand in comparison to other ports. They can also use the outcome measures to develop strategic and operational decisions to stay competitive in the global market of maritime transportation.

3.3.1 Key Performance Indicators (KPIs)

The first step toward measuring the SPI is to identify a comprehensive set of KPIs for quantifying port performance in each smart port activity domain. Tables A.2, A.3, A.4, and A.5 show the KPIs we collected from the literature for measuring port performance (see Appendix A). We have adopted KPIs from several sources, as shown in Table 3.4 [16, 119, 120, 121]. We

Table 3.4: Information on the collected KPIs

Category	Study				Total number of KPIs
	MedMaritime SMARTPORT	Anto, P. et al.	Maigret, A. et al.	Perera, M. A. P. et al.	
Operations	✓	✗	✗	✓	29
Environment	✓	✗	✓	✓	27
Energy	✓	✗	✓	✓	17
Safety and Security	✓	✓	✗	✗	15

borrowed all the 68 KPIs of MedMaritime Smart Port: 26 KPIs related to SOI sub-domains, 2 KPIs for SSSI, 16 KPIs for quantifying SEgI, and 24 KPIs related to SEnI. Then, we selected and added the remaining KPIs from other related sources to enhance the capability of the SPI in measuring all the smart port domains and sub-domains.

3.3.2 SPI Formulation

The performance of a smart port is quantifiable through four indices we present here: Smart Operations Index (SOI), Smart Energy Index (SEgI), Smart Environment Index (SEnI), Smart Safety and Security Index (SSSI). Because the range of values can be quite different from one KPI to the next, the values must be rescaled so that the KPI values are comparable in the combined SPI. Standardization and normalization are the two common approaches for rescaling the data. In normalization, the data is modified to take values between 0 and 1 (Equation (3.3.1)). Normalized data is calculated by Equation (3.3.1) in which x is the original data, x_{min} is the minimum x value in the data set, and x_{max} is the maximum x value, as:

$$x_{normalized} = \frac{x - x_{min}}{x_{max} - x_{min}}. \tag{3.3.1}$$

The normalization maps the data to positive values, while standardization may result in negative values. In this paper, the normalization equation (Equation (3.3.1)) is used to transform the original data. The KPIs can be modified in such a way that if a higher KPI value is preferred, the normalized value can be used as is. But, if less value for the KPI is preferred, the KPI value can be multiplied by -1 (see Equation (3.3.2)). For instance, higher values of port productivity (e.g., annual throughput) and lower values of air emission (e.g., total annual air emission) are more desirable. So, we keep positive the productivity value but we multiply the air emission value by -1. As a result, the positive productivity value increases the total SPI while the negative emission value reduces it. Each of the four indices (SOI, SEgI, SEnI, and SSSI) is calculated as a function of the relevant KPIs (Equations (3.3.3)-(3.3.6)). For instance, in Equation (3.3.3), α_i's take positive values and the summation of them should be equal to 1. Hence, SOI is calculated as the convex combination of the modified KPIs. Equations (3.3.4) through (3.3.6) have the same structure as Equation (3.3.3). Finally, SPI is quantified using Equation (3.3.7). Note that j refers to the smart port activity domains, i.e., $j \in$ {1: operations, 2: energy, 3: environment, 4: safety and security}, the rescaled value of i^{th} KPI of j^{th} category is k_{ij} (n_i is number of KPIs for measuring port performance in i^{th} smart port activity domain) and the signed value of i^{th} rescaled KPI of j^{th} category is k'_{ij}. The terms are calculated by

$$k'_{ij} = \begin{cases} -k_{ij}, & \text{lower values of } k_{ij} \text{ are preferable} \\ k_{ij}, & \text{higher values of } k_{ij} \text{ are preferable} \end{cases}, \tag{3.3.2}$$

$$SOI = \sum_{i=1}^{n_1} \alpha_i k'_{1i}, \quad \sum_{i=1}^{n_1} \alpha_i = 1, \quad \alpha_i \geq 0, \forall i = 1, ..., n_1, \tag{3.3.3}$$

$$SEgI = \sum_{i=1}^{n_2} \beta_i k'_{2i}, \quad \sum_{i=1}^{n_2} \beta_i = 1, \quad \beta_i \geq 0, \forall i = 1, ..., n_2, \tag{3.3.4}$$

$$SEnI = \sum_{i=1}^{n_3} \gamma_i k'_{3i}, \quad \sum_{i=1}^{n_3} \gamma_i = 1, \quad \gamma_i \geq 0, \forall i = 1, ..., n_3, \tag{3.3.5}$$

$$SSSI = \sum_{i=1}^{n_4} \delta_i k'_{4i}, \quad \sum_{i=1}^{n_4} \delta_i = 1, \quad \delta_i \geq 0, \forall i = 1, ..., n_4, \text{and} \tag{3.3.6}$$

$$SPI = \lambda_1 SOI + \lambda_2 SEgI + \lambda_3 SEnI + \lambda_4 SSSI,$$
$$\sum_{i=1}^{4} \lambda_i = 1, \quad \lambda_i \geq 0, \forall i = 1, 2, 3, 4. \tag{3.3.7}$$

Each of the SPI indices mentioned above (Equations (3.3.3)-(3.3.7)) requires the values for weight parameters, e.g., $\alpha, \beta, \gamma, \delta, \lambda$. These values must be provided to the equations beforehand, and they can be determined by expert opinions. Analytic Hierarchy Process (AHP) or Analytic Network Process (ANP) are two common methods to calculate the weight parameters and this calculation is beyond the scope of this paper [122, 123, 124].

Since KPIs are normalized as in Equations (3.3.1) and (3.3.2) for the purpose of index calculations, each resulting KPI can take a value between -1 and 1. According to Equations (3.3.3) through (3.3.6), all indices are convex combinations of the associated scaled KPIs; hence, they also range between -1 and 1. As a result, the SPI values are in the range of [-1,1].

3.4 Using SPI to Evaluate and Compare International Port Performance

3.4.1 Comparison of Fourteen International Ports

Fourteen ports are selected among the world's busiest ports in terms of numbers of annual TEUs. The selection of the ports is based on two criteria: the availability of the data from the related port authority website and diversity in terms of ports locations.

3.4.1.1 Data Collection and SPI Measurements

We have collected relevant data for fourteen ports from their websites to illustrate the use of the proposed method. We have experienced that not all ports publish the necessary data to calculate all KPIs discussed in this paper, but we were able to obtain publicly available data to compute 8 KPIs (see Appendix, Table A.2, KPIs 1, 3, 5, 7, 9, 11, 22, and 23). These KPIs are all related to measuring *Productivity*, SOI. Thus, we modified the index measurement approach presented in the previous section to quantify other activity domains as follows: if the port has stated and explained related activities to each smart port activity domain in the port website, we have assigned the value of 1 to the sub-domain index value, and for those areas that are not mentioned in the website, we have not assigned any value. For instance, for measuring SOI, we can calculate the *Productivity* by KPIs (e.g., annual throughput (TEU/meter of container quay)), but the data is not available for quantifying the *Automation* and *Intelligent Infrastructure*. So, if the port website mentions ongoing activities in these two areas, we assign the value of 1 to each. For increasing the preciseness of this modified approach, we divided *Intelligent Infrastructure* into two categories of *Software (IIS)* and *Hardware (IIH)*. We also divided *Integrated Monitoring and Optimization Systems* into two categories of *Integrated Monitoring Systems for Safety* and *Integrated Monitoring Systems for Security*.

There are four categories ($n_1 = 4$) in calculating SOI (*Productivity, Automation, IIS, and IIH*) in Equation (3.3.3). By assuming equal weights among these categories, the value of α_i is 1/4, for $i \in \{1,2,3,4\}$. For computing SEgI (Equation (3.3.4)), there are three categories (i.e., low energy consumption, producing/use of renewables, and energy management); hence, $n_2 = 3$ and $\beta_i = 1/3$ for i $\in$ {1,2,3}. Categories included in Equation (3.3.5) are environmental management system, emissions and pollution control, waste management, and water management; $n_3 = 4$ and $\gamma_i = 1/4$ for i $\in$ {1,2,3,4}. Regarding safety and security index quantification (Equation (3.3.6)), there are four categories (i.e., safety management system, security management system, integrated monitoring system for safety, and integrated monitoring system for security); $n_4 = 4$ and $\delta_i = 1/4$ for i $\in$ {1,2,3,4}. Putting these all together, the SPI index is calculated as in Equation (3.3.7) by assuming equal parameter weights. The other measurement steps in this example are the same as the approach outlined in Section 3 and SPI values take values in the range of [-1,1].

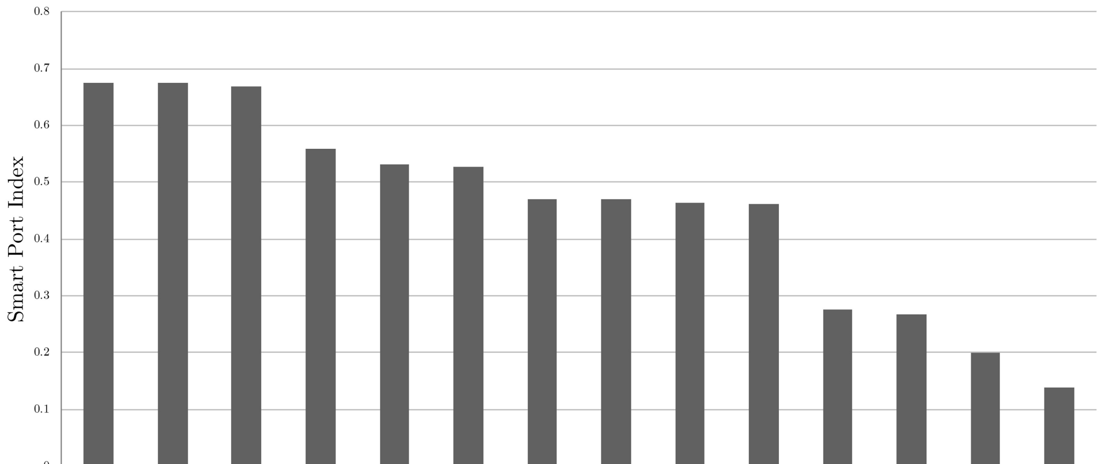
3.4.1.2 Effects of Region-Specific Variables on the smartness of the ports

The data analysis in our study has three objectives: to calculate and compare index values of the selected ports, to analyze why a port received the associated score, and to make suggestions for improving port performance. In this numerical example, the Hamburg Port Authority received the highest SPI value of 0.6756, while the Port of Hong Kong received the lowest SPI value of 0.1388 (Figure 3.2). Moreover, our approach reveals that ports have paid different levels of attention to each smart port activity domain (see Appendix A, Figure A.1). For instance, the Port of Singapore

Table 3.5: Regression analysis showing the effect of region-specific variables on SPI (α = 5%)

Variable	GDP per capita ($ thousands/# of inhabitants)	R&D expenditure (% of GDP)	Energy intensity of the economy (kg of oil equivalent/GDP)
Coefficient	0.0086	0.0026	-0.0019
p-value	0.0129	0.0196	0.0003
R-square	0.5154	0.4715	0.7904

has initiated and declared more smart actions in the port operations than the environment, while in the Port of Jeddah, smart actions have penetrated more in safety and security than in operations.



	Port of Hamburg	Port of Rotterdam	Port of Antwerp	Port of Busan	Port of Singapore	Port of Los Angeles	Port of Vancouver	Port of Jebel Ali	Port of New york and New jersey	Port of Houston	Port of Shanghai	Port of Tanjung Priok	Port of Jeddah	Port of Hong Kong
■ SPI	0.6756	0.6751	0.6680	0.5593	0.5304	0.5271	0.4711	0.4693	0.4642	0.4611	0.2750	0.2675	0.2005	0.1388

Figure 3.2: Comparison of Smart Port Index for 14 ports

The second step of the empirical study is to find the causes of the varied index values. We analyzed the impact of the geographical (Figure 3.3, Figure 3.4), economic, political, and energy-related factors on the port smartness (Table 3.5). On average, European ports seem to be more conscious about factors included in the SPI calculation as compared to Asian ports (Figure 3.3, Figure 3.4). We can observe that there exists a meaningful correlation between the smart port interventions in environmental and energy-related aspects and geographical variables; European ports have expressed greater interest in eliminating port environmental and energy-related issues than Asian and North American ports. Asian ports have high SOI values and have shown greater tendency to increase the productivity and enhance port operations compared to the other smart port activity domains (Figure 3.4).

To measure the effect of economic and energy-related factors on the SPI value, we considered country gross domestic product (GDP) per capita, R&D expenditure per capita, and energy intensity of the economy. The selection of these variables was based on data availability (data source: [125]). We performed linear regression analysis to study the correlation between each variable and the SPI value. Positive regression coefficients show the positive correlation between the variable (and so the factor) and SPI. On the other hand, negative coefficients indicate a negative correlation between them.

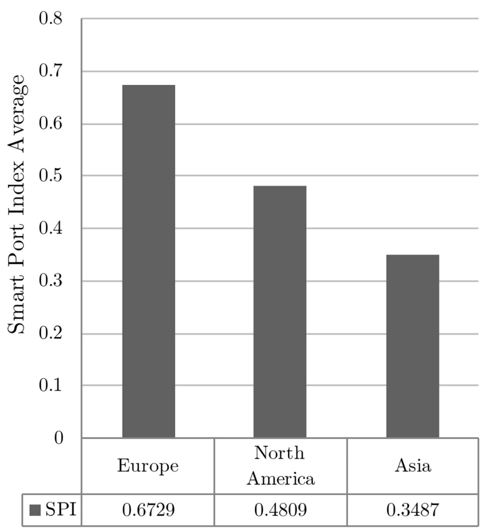


Figure 3.3: SPI by region

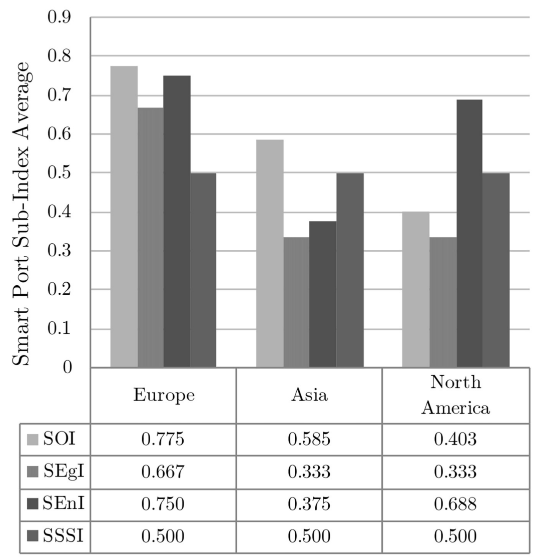


Figure 3.4: Smart sub-indices by region

Figures 3.5, 3.6, and 3.7 visualize the effects of GDP, R&D expenditure, and energy intensity of the economy on the SPI values by linear regression. In Figure 3.5, we observe that there is a positive correlation between port SPI value and country GDP per capita. This indicates that ports located in wealthier countries have higher SPI values. Figure 3.6 shows a positive correlation between country R&D expenditure per capita and the port SPI value. We can interpret that if a country is more open to innovation and higher education systems, then the country's ports are more interested in the implementation of new technologies and innovative approaches. Figure 3.7 visualizes a negative correlation between the amount of energy consumption in the country per GDP and SPI. Higher energy intensity values indicate that higher industrial output and effort were required for production and service. This means either the industries in the country are not productive or energy efficient. We can observe how SPI value reduces as the energy intensity increases in Figure 3.7.

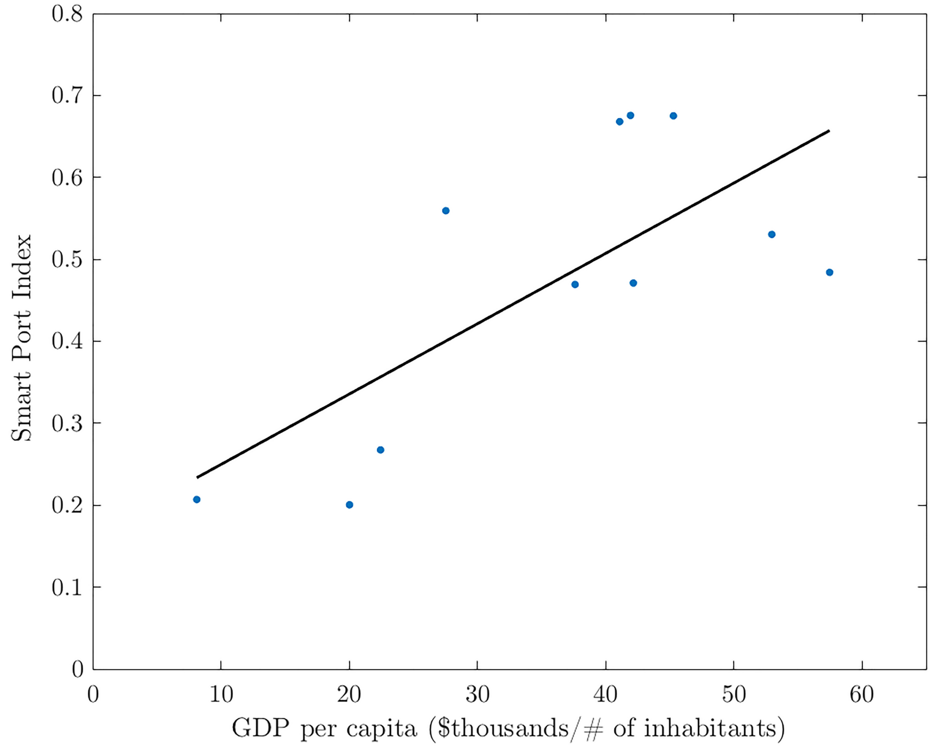


Figure 3.5: GDP effect on SPI value

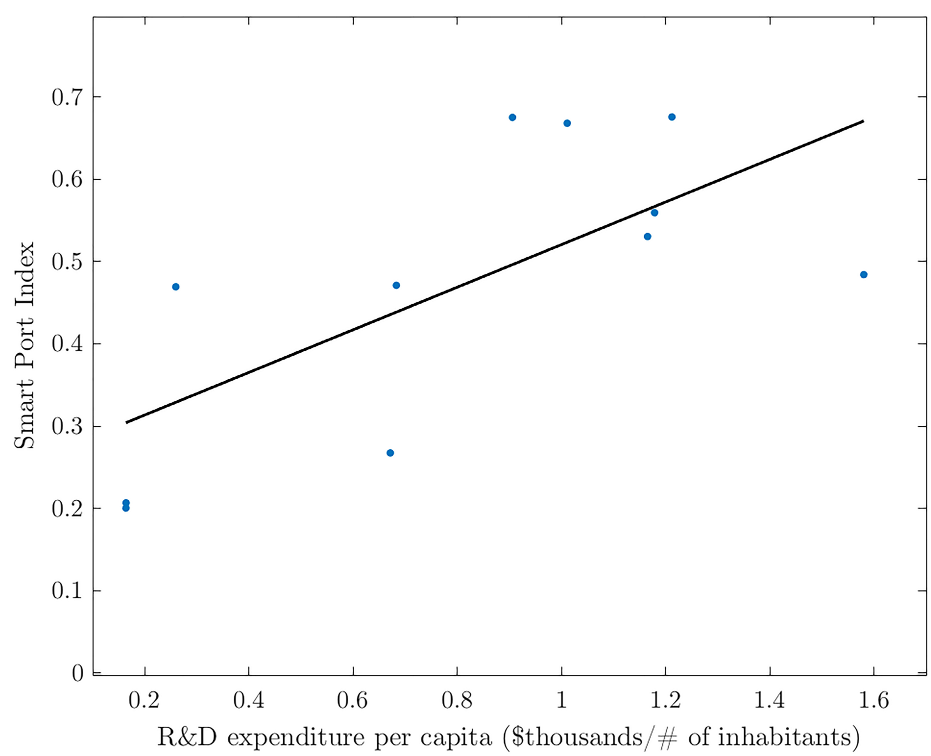


Figure 3.6: R&D expenditure effect on SPI value

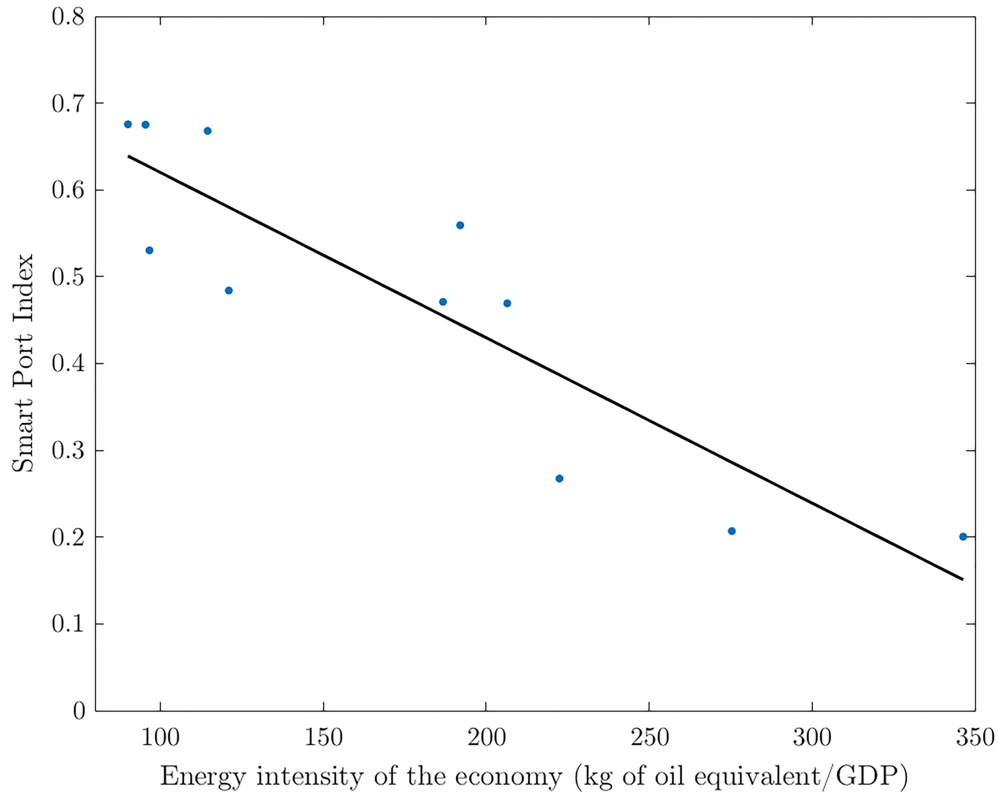


Figure 3.7: Energy intensity of the economy effect on SPI value

3.5 Conclusion

Smart port is a wide concept that encompasses various aspects of port activities. However, it has so far received limited attention from academic researchers. Despite the recent growing interest in the topic, efforts are required to identify benchmarks at the international level, and to find improvement opportunities in ports. In this scenario of limited empirical evidence and hype on smart ports, this paper can be considered the first attempt to provide a comprehensive definition of a smart port and an empirical assessment of current trends at the international level. To this end, four main activity domains (i.e., operations, energy, environment, and safety and security) and the related sub-domains of a smart port were identified based on smart port best practices; afterward, the Smart Port Index was developed as the convex combination of the sub-indices.

Index calculation is achieved mainly through measurement of the KPIs collected from the literature. The numerical example included the study of 14 ports selected among the top 100 busiest ports in the world in terms of the total number of annual TEUs. Note that we have experienced limited availability of data for some KPIs described in this paper. Port selection criteria were the availability of data given on the ports websites and diversity in the location of the ports. After index measurements, an analysis was conducted in order to understand the relationship between the geographical, governmental, economic, and energy-related variables, and the dependent SPI variable. It was noticed that regional variables and government policies can affect the port performance and that in general, ports located in countries that are wealthier, open to innovation, environmentally-friendly, and energy efficient have higher SPI values.

In the process of achieving the above results, the paper explains two issues. First, current smart port initiatives have different pillars, some of which overlap. Some of the ports are conducting multipurpose projects, while the others have targeted special areas such as ICT penetration into the port operations. It has been noticed that European ports have relatively comprehensive approaches and they are more conscious about port environmental and energy aspects in comparison to the other ports. This can be traced back to the environmental standards that the European Union mandates different organizations to follow [126]. In this study, we attempted to conceptualize a smart port that includes various aspects of port activities and incorporates important areas of concern such as the environment or energy.

Secondly, adequate information and data for quantifying ports smartness are not available. This is due to either port policies and their reluctance to share the detailed information or the lack of focus on some smart port activity domains. We reduced the impact of this limitation on the results by selecting ports with the highest level of data availability and modifying the indices computation approach.

For future research, one can investigate other possible activity domains to be included in the smart port concept such as sustainability, human resources (e.g., knowledgeable employees, creativity, training opportunities), and institutional aspects (e.g., corporate governance, harmony with the community, supply chain partnerships). Moreover, if one has access to more comprehensive data for computing more KPIs, the empirical research can be extended to enhance the analysis presented in this paper. Furthermore, there is a need to further explore both the barriers of implementation and impacts of a smart port on the related matters; for instance, we can target topics such as the impact of smart ports on traditional institutional and human factors and the influence of smart ports on cities and the surrounding municipalities.

Chapter 4

Enabling Smart Ports Through the Integration of Microgrids: A Two-Stage Stochastic Programming Approach

4.1 Introduction

With the world trade and globalization demanding maritime transportation, maritime ports have faced ever-increasing pressure to optimize their performance and deliver more effective and secure flows of goods worldwide. Unlike other industrial systems, as the regional multimodal intersection of global supply chains, a port operates in the context of a complex network of interconnected transportation, industrial, and civil infrastructure, and thus faces multifaceted challenges to provide efficient, cost-effective and sustainable means of transporting goods globally. There is a growing global trend among port entities that new technology-based solutions need to be adopted to facilitate the transformation of conventional ports into high-performance ports to support the ever-increasing import and export tonnage and the resulting traffic while reducing the potential impact on the environment and public health as well as vulnerability to extreme natural and man-made disasters. The port industry is undergoing the transformation to a “smart port" as a result of technological advancements and changing customer expectations. This transformation is an essential step to move the port industry toward a new era of reliability, sustainability, efficiency, and energy dependency that will further contribute to sustaining economic growth and spreading prosperity throughout the world.

Molavi et al. [127] introduced a concept of smart port that involves a variety of advanced digital technologies consisting of monitoring, control, automation, and intelligent equipment and applications working together, to optimize the port operations and revitalize the existing infrastructure for a cleaner and strengthened port. Among many, the port industry and researchers have identified microgrids as one of the primary technology enablers for this vision.

A microgrid is a relatively small-scale localized energy network that features an effective integration of high penetration level of Distributed Energy Resources (DERs), such as renewable energy resources, energy storage devices, and controllable loads [7]. A microgrid can operate separately from the larger electrical grid as a self-sustainable entity during extreme weather events or contingencies and reconnect once the contingencies are cleared. Compared with the traditional centralized operation paradigm of bulk power systems, microgrid offers various advantages such as increased efficiency and power quality, reduced cost, enhanced resiliency, and a more reliable, continuous, controllable and clean power supply ([39], [128]).

It is envisioned that microgrids add the missing “piece" which the port authorities and agencies have been searching for a long time to make traditional ports smart. For the first time, microgrids, as the underlying energy backbone, provides a natural host and a technology hub to support the latest technology-intensive and information-centered economy models that the port entities are actively adopting as a part of the port modernization and electrification initiative. The recent advancement of DERs and their dramatic cost declines have made microgrids both technically and economically feasible and viable. The distributed and localized nature of microgrids, along with the secure, high-quality, and green energy they provide, opens up opportunities for technology integration, capacity expansion, sustainability enhancement, and business continuity to further improve the port's smartness.

In this paper, we discuss how the adoption of microgrids can systematically improve a port's performance in its four main activity domains: operations, environment, energy, safety and security. Then we propose a set of Smart Port Index (SPI) metrics [127] to quantitatively evaluate the benefits that microgrids could contribute to those domains. This index is expected to impact the decision-making process for both the port authorities and government/regulatory authorities. More specifically, the use of this index enables port authorities to measure and investigate a port's performance for different applications, based on which future strategic plans and organizational policies can be developed for long-term growth and resource optimization. For the regional/state government, the potential benefits include regulation and policy success for social well-being, quality of life, and sustainable development, as well as critical insights in managing large consumer-facing businesses that have been impacted by disruptive technological changes. Overall, we are aiming to provide criteria for answering the question of: *for a port entity, is it a meaningful decision to integrate the microgrid?*

A two-stage stochastic mixed-integer programming model is developed to demonstrate how this index can significantly improve the smartness of the port when it is used in the context of port operation and management during the planning. The model consists of two stages: 1) an *investment* master problem to determine the optimal installation status of the DERs, and 2) a multi-objective *operation* planning subproblem to decide on the optimal hourly power generation, load shedding, and power flow between the microgrid and the utility grid (i.e., main grid). The stochastic model considers the inherent operation uncertainties associated with renewable power generation and power outage. Benders decomposition and Lexicographic Goal Programming are proposed to solve the model. Case studies are then performed to evaluate the use of microgrid at the Barbours Cut Terminal in the Port of Houston.

The contributions of this paper include:

- Proposed a rigorous and logical process to evaluate how microgrids can systematically address the current challenges the ports are facing and enhance their performance in different activity domains. Our work is one of the pioneering research efforts to evaluate and quantify the benefits provided by microgrids to create sustainable value for a smart port.

- Proposed and applied a set of SPI metrics to evaluate how the introduction of microgrids can holistically improve the performance of a port. This provides an analytic approach for key stakeholders (regulators, port authorities, industrial partners) to evaluate how a microgrid can help a port meet its performance objectives based on a list of factors.

- Without the loss of generality, policy studies are performed in this paper, paired with realistic data, to demonstrate and verify how the utilization of the proposed SPI can effectively improve the operation of the Barbours Cut terminal at the Port of Houston compared with conventional microgrid planning approach that does not consider the domain-specific port features and demands.

The remainder of this manuscript is organized as follows. Section II explains the SPI for the port microgrid. Section III formulates the mathematical model. The model is tested under different operation scenarios and policy settings in Section IV. Conclusions are drawn in Section V.

4.2 Smart Port Microgrid Index

4.2.1 Background

Electricity has become the dominant medium to integrate, store, and transport energy, and thus is playing a critical role in the global energy supply chain. With large numbers of operations demanding significant power, there are many existing and ongoing efforts around the world to create integrated energy, sustainability, and business solutions that incorporate the concept of microgrids.

In the United States, Port of Los Angeles (POLA) has recently invested $27 million in microgrid development and distributed clean energy resource technologies. As a demonstration project, a microgrid that incorporates a 1 MW solar PV array, an on-shore 2.6 MWh battery storage system, and the associated electrical infrastructure upgrade has been completed in the Omni Terminal and expected to serve as a model for the modernization of 26 other marine cargo terminals at POLA. Port of Long Beach (POLB) has been evaluating microgrid development to support the port's Energy Island Initiative. The evaluation concluded that the development of a microgrid would effectively assist POLB's transition toward renewable energy and serve the port's needs for energy reliability, power quality, and economic stability ([34], [35]). In 2018, Port of San Diego was awarded $5 million grant from California Energy Commission for the installation of a renewable-energy-based microgrid at the Tenth Avenue Marine Terminal [36]. The project includes the installation of solar PV panels, battery energy storage, a microgrid controller, and other infrastructure improvements to provide back-up power to port-operated facilities and support military deployment activities.

In Europe, the city of Rotterdam has been partnering with General Electric to transform the Port of Rotterdam into a virtual power plant (VPP) that consisting of a coordinated cluster of microgrids. Built on thermal and renewable power production, the Port is expected to function as a smart energy grid with reduced emissions, enhanced demand-side management, and increased energy efficiency [37]. Microgrids can be especially helpful where shore-to-ship power transfer is offered to reduce the emissions and noise levels of vessels docked in port. As a representative example, Port of Gothenburg has the first 50/60 Hz shore connection in Sweden and shore-side power supply to a vast number of cargo vessels while at berth featuring fully automated power transfer. Port of Dalian in China, Port of Fincantieri in Italy, Port of Ystad in Sweden, and Port of Moin at Costa Rica, among others, are instances of a broader effort to electrify the processes, services, and equipment [38].

4.2.2 Targeted Port Activity Domains

A smart port consists of four main activity domains: operations, environment, energy, and safety and security. This section shows how the adoption of a well-designed microgrid can potentially enhance the performance of a port in those activity domains.

- *Operation*: The main operation of the port is to load and unload cargo and containers from received vessels and handle the process of transporting the cargo to warehouses or other destinations. To support the ever-increasing import and export tonnage and cargo transportation resulted from the continuing economic globalization, a smart port microgrid is expected to meet a port's dynamic energy demand in an adaptive, flexible and expandable manner. The abundant generation and distribution capacity assures that the demand of terminal equipment, such as cranes and manifolds can always be met, thus improves the productivity of terminal operators to handle large volumes of cargo and truck traffic, reduce container dwell time and terminal congestion, and thus greatly enhance the throughput of the operation to meet the growing capacity demand ([129], [130]).
- *Environment*: Environmental impacts of the port activities reduce social welfare and pose a

threat to the survival of living creatures. Therefore, port authorities are facing constant critiques of producing a significant quantity of pollutants and contributing to a range of biophysical problems to the site and the neighboring residential communities. This has caused critical challenges for port management and menaced the ports' endurance in the future competitive era. Towards this end, a microgrid-based energy infrastructure encourages the collaboration of sustainable initiatives, ecological regenerations, and zero-net energy goals by utilizing renewable and clean energy sources through purposeful planning and preparation. Providing environmentally responsible energy promotes the port's role in meeting the imperative to combat climate change and address the existing environmental problems, and thus minimizes the port's negative impact on the environment and public health ([43], [131], [44]).

- *Energy*: In the face of ever-increasing energy consumption and costs, a smart port microgrid provides a unique opportunity for integrating the latest smart grid technologies to improve energy functionality. For example, advanced smart meters with higher connectivity and stronger sensing capabilities, cost-effective cyber infrastructure and scalable protocols, and low-cost, low-loss power electronics converters can be seamlessly incorporated to enable improved management and control of loads and energy consumption. This allows the port to be constantly operated in an efficient and economical way to decrease energy consumption and mitigate costs while meeting the power demand and power quality requirement from different sectors and facilities. In addition to maintaining self-sustainability, a smart port microgrid will be able to participate in the energy market and provide excellent investment and economic viability through smartly managing the power exchange between the main grid and itself. Additionally, there are plenty of opportunities in integrating renewable generations at ports, such as wind and solar power and even bioenergy, because often large quantities of biomass accumulate in and around the harbor areas. This is an efficient approach to land use in ports and facilitates the reduction in the consumption of limited fossil fuels. Therefore, microgrid installation is believed to be one of the best approaches to supplying the power associated with onshore-power-supply, all-electric ships, electric trucks and heavy-duty vehicles, electric harbor craft (e.g. tugboats), and electric cargo handling equipment (e.g. yard tractors, ship-to-shore cranes, electric rubber tire gantry cranes (ERTG), electric rail mounted gantry cranes) ([40], [41]).

- *Safety and Security*: Ports can be vulnerable to a sequence of safety and security issues during a power outage. Equipped with local distributed generation and energy storage resources, a smart port microgrid is able to add significant power safety and security to the ports as it enables continuous and seamless power supply for persistent monitoring and control of facilities, prevents accidents and incidents that may occur during the absence of power, maintains critical loads such as fire stations, information and communication facilities, electricity-dependent security measures (e.g. electric gates, electric fences, surveillance cameras), and emergency transportation systems along the ship channel. Eventually, a microgrid creates redundancy and back-up power to increases port preparedness and resilience to prolonged outages. This is particularly important due to the recent trend that weather-related extreme events are happening in higher frequency and severity which have become the new norm ([129], [130], [132]).

4.2.3 Microgrid-Based Smart Port Index

SPI uses four sub-indices for measuring the performance of a smart port in the aforementioned four key activity domains. Those sub-indices are named Smart Operations Index (SOI), Smart Energy Index (SEgI), Smart Environment Index (SEnI), Smart Safety and Security Index (SSSI), respectively. SPI is then formulated as a convex combination of these four sub-indices.

This section provides further context to the specific design attributes of each operation domain concerning microgrid integration. Tables 4.1, 4.2, 4.3, and 4.4 present the KPIs that we use for quantifying the effect of microgrid implementation on the smart port performance.

Table 4.1: KPIs for quantifying Smart Operations Index

1. Annual TEUs/Total terminal area
2. Annual cargo tonnage/Total terminal area
3. Annual throughput in TEU per number of cargo handling equipment, trucks, locomotives, and harbor craft
4. Total TEUs per number of container vessels calling the port

Table 4.2: KPIs for quantifying Smart Energy Index

1. Total energy consumption (primary energy) by port authority per total port area (kWh/m^2)
2. Total energy consumption (primary energy) by the container terminals per total terminal area (KWh/m^2)
3. Percentage of energy from renewable resources
4. Energy saved due to conservation and efficiency improvements

Table 4.3: KPIs for quantifying Smart Environment Index

1. Emissions from all port activities per total port area
2. Total annual GHG per vessels calling the port

Table 4.4: KPIs for quantifying Smart Safety and Security Index

1. Annual number of nautical accidents (significant or incidents in areas under the jurisdiction of the port authorities)
2. Annual number of failure to comply (port regulations, industry safety standards, etc.)
3. Annual number of fires and explosions (either nautical or industrial)
4. Annual number of security issues

KPIs should be normalized and preprocessed before being used for the sub-index calculations. Each sub-index is a convex combination of the associated processed KPIs [127]. Here, the KPIs are preprocessed to make sure that sub-indices take values in the range of [0,1]. Hence, SPI always varies between 0 and 1 throughout this paper.

4.3 Problem Formulation and Solution Methodology

Table 4.5 shows the notation used in problem formulation and developing the optimization model.

4.3.1 Modeling the Benefits of Microgrid for the Port Performance

Based on the previous discussion, it is evident that ports are critical infrastructure with significant power demands, and their successful operations heavily rely on high-quality and reliable power supplies. The first benefit of microgrid deployment is that it encourages effective use of electricity and enables better energy management by differentiating types of loads and establishing their priorities ([133], [134]). Hence, we divide the port power demand into three types: critical loads (denoted by superscript V), high priority loads (referred to by superscript H), and low priority loads (indicated by superscript L) as follow:

$$D_{bht} = D^V_{bht} + D^H_{bht} + D^L_{bht} \quad \forall b, h, t. \tag{4.3.1}$$

Critical loads in ports mainly consist of power demand for safety and security purposes and cannot be shed. These loads are only subject to the power outage. High priority loads include all the essential load that is necessary for the successful operation of the port and handling the containers and cargo (e.g., the power required for electric cranes, onshore power supply, and electric trucks). High priority loads are both subject to load shedding and power outage. Low priority loads are those that are considered non-essential and thus do not impact the throughput and main operation of the port (e.g., extra power consumption in buildings and offices). Same as high priority loads, these

Table 4.5: Nomenclature

t	Index for year
h	Index for month
b	Index for hour
i	Index for DERs
ch	Superscript for energy storage charging mode
H	Superscript for high priority loads
L	Superscript for low priority loads
V	Superscript for critical loads
dch	Superscript for energy storage discharging mode
T	Subscript for total values over the planning horizon
rs	Subscript for energy consumption from renewable sources
eg	Subscript for the reduced load on the main grid
ls	Subscript for the curtailment of low priority loads
ω	Index for scenarios
G	Set of dispatchable units
W	Set of nondispatchable units
S	Set of energy storage systems
Ω	Set of scenarios
c	Generation price for dispatchable units
CC	Annualized investment cost of generating units
CP	Annualized investment cost of storage - energy
CE	Annualized investment cost of storage - power
C^{max}	Rated capacity of energy storage systems
D	Load demand
D^{max}	Annual peak load
K	Large positive constant
P^{max}	Rated power of DERs
P_M^{max}	Flow limit between microgrid and the main grid
κ	Coefficient of present-worth value
ρ	Market price
υ	Value of lost load (VOLL)
η	Energy storage efficiency
λ	Maximum allowable load shedding (% of load)
γ	Weight factors in SEgI calculation
Pr_M^{Outage}	Probability of main grid power outage
RS	Energy generated or consumed at port from renewable sources
EM	Emission production
SSI	Number of safety and security incidents due to power loss
q	Number of handled containers
B	Budget
COL	Cost of load shedding
x	DER investment state
P	DER output power
P_M^+	Power bought from main grid
P_M^-	Power sold to main grid
LS	load shedding

can are subject to both load shedding and power outage. However, it is commonly assumed that the value of lost load associated with low priority loads is much lower than the higher priority ones.

For managing the power balance for each type of demand, it is necessary to define the variables associated with each demand type. These variables include power generation from DERs, charged and discharged power from the storage units, power flow between the microgrid and the main grid, as well as the load curtailment. Based on the provided explanations and similar to what is described for D_{bht} in Equation (5.2.1), variables P_{ibht}, P^{ch}_{ibht}, P^{dch}_{ibht}, $P^{+}_{M,bht}$, $P^{-}_{M,bht}$ each can be divided into three sets of variables associated with critical, high priority, and low priority loads. The set of variables corresponding to load shedding (i.e., LS_{bht}) each consists of two sets of variables related to high priority and low priority loads.

For the high priority loads, the on-site generation capacity expansion by deploying microgrid effectively enhances the port operation, which leads to increased annual throughput and can be reflected by the KPIs in Table 4.1. The throughput of the port operations is commonly measured by either Twenty-Foot Equivalent Unit (TEU) for the number of containers or by cargo tonnage for the weight of the cargo. Cargo tonnage can be estimated by TEUs. Therefore, the Smart Operations Index (SOI) can be represented by the total handled containers (the multiplication of the number of handled containers per supplied power and the total amount of satisfied power demand) divided by the desired value for the total handled containers during the planning horizon (4.3.2). SOI is calculated as

$$
\begin{aligned}
SOI \quad &= \quad \frac{\sum_b \sum_h \sum_t q_{bht} D^{H}_{bht}}{q^{max}_{T}} \\
&\quad - \frac{\sum_b \sum_h \sum_t q_{bht} (LS^{H}_{bht} + Pr^{Outage}_{M,bht} P^{H,+}_{M,bht})}{q^{max}_{T}}. \qquad (4.3.2)
\end{aligned}
$$

Note that the port power demand, D_{bht}, varies continuously. Therefore, its value can alternate based on specific load growth patterns for each time slot throughout the planning horizon.

There are two variables for measuring KPIs in Table 4.2 that are affected by microgrid installation: net energy consumption and renewable energy generation. Hence, we define the Smart Energy

Index (SEgI), as a measure of integrating the latest energy-related functionalities, in the form of a convex combination of the three terms: 1) renewable generation from both DERs within the port microgrid and the main grid, 2) energy consumption reduction as seen by the main grid, and 3) energy efficiency improvement (Equation (4.3.3)). Note that the power supply from the main grid is associated with a probability of outage. The first term in Equation (4.3.3) refers to the renewable generation from all of the sources divided by the goal value for the total renewable generation (i.e., RS_T^{max}). The second term measures the energy consumption reduction during the entire planning horizon due to on-site generation and storage resources as well as net energy usage conservation such as demand-side management techniques, given the microgrid's ability to control electricity imports by utilizing the on-site generation and storage. The third term is the cost resulted from curtailing low priority loads divided by the maximum load shedding cost (COL). Maximizing this term increases the portion of load shedding cost associated with low priority loads to assure the load shedding operation comprises mostly of low priority loads. Coefficient terms γ_{rs}, γ_{eg}, and γ_{ls} in this equation can be determined based on the relative importance of the renewable generation, reduction in the load demand as seen by the main grid, and saving energy by reducing low priority loads. Coefficient terms γ_{rs}, γ_{eg}, and γ_{ls} vary in the range of [0,1] and $\gamma_{rs} + \gamma_{eg} + \gamma_{ls} = 1$ in

$$\begin{aligned} SEgI \quad = \quad & \gamma_{rs}\Big(\frac{\sum_b \sum_h \sum_t \sum_{i \in G,W} RS_i P_{ibht}}{RS_T^{max}} \\ & + \frac{RS_M(1 - Pr_{M,bht}^{Outage})P_{M,bht}^+}{RS_T^{max}}\Big) \\ & + \gamma_{eg}\Big(\frac{\sum_b \sum_h \sum_t D_{bht}}{D_T} - \frac{\sum_b \sum_h \sum_t (1 - Pr_{M,bht}^{Outage})P_{M,bht}^+}{D_T}\Big) \\ & + \gamma_{ls}\Big(\frac{\sum_b \sum_h \sum_t \upsilon_{bht}^L LS_{bht}^L}{COL_T^{max}}\Big). \end{aligned} \tag{4.3.3}$$

Under the assumption that each power source is associated with an emission rate per power provided, we define the Smart Environment Index (SEnI) as the mitigated emission rate (Equation (4.3.4)). This equation measures the gap between the desired value of SEnI (i.e., $SEnI^{max}$) and the total amount of the emission produced by the different sources per maximum potential amount of emission (i.e., EM_T^{max}). Maximizing this sub-index reduces the total emission of a port (second term in the Equation (4.3.4)). This equation can be applied to different air pollutants (based on the goals of the port authority) or can be used to measure all of them together by using a simple scaling method (e.g., using CO_2e which is CO_2 equivalent representation of the other greenhouse gasses) [135]. $SEnI$ is calculated as

$$\begin{aligned} SEnI &= SEnI^{max} \\ &- \frac{\sum_b \sum_h \sum_t \sum_{i \in G,W} \Big(EM_i P_{ibht}}{EM_T^{max}} \\ &+ \frac{EM_M (1 - Pr_{M,bht}^{Outage}) P_{M,bht}^{+} \Big)}{EM_T^{max}}. \end{aligned} \tag{4.3.4}$$

It is expected that the enhanced reliability and resiliency of the power supply by microgrids leads to a reduced number of safety and security incidents caused by power outages. Thus, the Smart Safety and Security Index (SSSI) is quantified by the reduced number of safety and security incidents (Equation (4.3.5)). The first term in this equation is the goal value of SSSI (i.e., $SSSI^{max}$) and the second term refers to the number of safety and security incidents that occur due to the loss of power (i.e., SSI) divided by SSI_T^{max} as in

$$\begin{aligned} SSSI &= SSSI^{max} \\ &- \frac{\sum_b \sum_h \sum_t SSI_{bht} Pr_{M,bht}^{Outage} P_{M,bht}^{V,+}}{SSI_T^{max}}. \end{aligned} \tag{4.3.5}$$

Note that based on our definition, all of the indices presented in Equations (4.3.2)–(4.3.5) take values in the range of [0,1] and their goal values are 1.

4.3.2 Uncertain Parameters in Microgrid Planning

The error of the renewable generation forecast is a major source of uncertainty. A high degree of renewable energy resources, commonly wind and solar energy, are utilized in microgrids that would produce power that is variable and stochastic [136, 137]. Another source of uncertainty is the probability of disruptions in the main grid. A grid-connected microgrid can switch to island mode to maintain uninterrupted functioning when there is a disturbance in the upstream distribution network. It can switch back to the grid-connected mode and resynchronize with the utility grid when the disturbance is cleared. Such disturbances are often random events, and therefore, in this paper, we use the outage probability to capture the effects of major outages in the main grid to the port.

4.3.3 Two-Stage Stochastic Mixed-Integer Model

To obtain the optimal decisions while dealing with the uncertainties, we propose an optimization approach in which two optimization stages are solved to address “Investment Planning" and “Operation Planning", respectively (Figure 4.1). The investment master problem on the first stage is formulated in the form of an integer programming model while the operation planning subproblem on the second stage is formulated as a linear programming model. The master problem determines the optimal installation status of the DERs while the subproblem determines the optimal mix of generation and schedule of the DERs, load shedding, and hourly flow between the microgrid and main grid. Benders Decomposition is implemented and at each iteration, feasibility and optimality cuts are introduced to improve the optimal solution of the master problem.

The investment master problem aims to determine the optimal installation mix of dispatchable, nondispatchable, and storage units. The corresponding optimization model includes

$$\max_{x_i} \quad E_\omega[Q_\omega(x_i)], \tag{4.3.6}$$

$$s.t. \quad D_t^{max} \leq \sum_{i \in G,W,S} P_i^{max} x_i \quad \forall t, \text{and} \tag{4.3.7}$$

$$x_i \in \{0,1\}, \quad i \in G, W, S. \tag{4.3.8}$$

The objective of the master problem is to maximize the expected value of the Q_ω over the set of scenarios (4.3.6). This term is associated with the subproblem objective function and will be

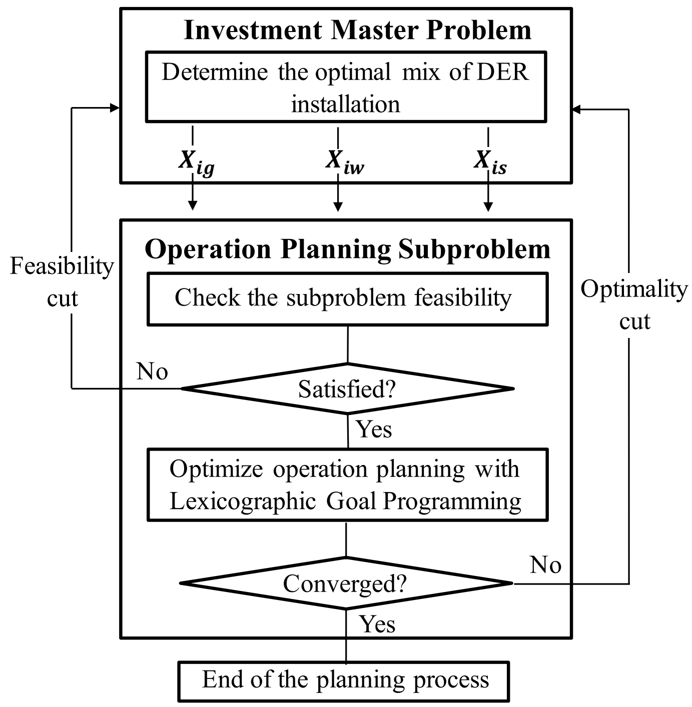


Figure 4.1: Proposed Microgrid planning

determined by the optimality cuts that will be added to the master problem. Constraint (4.3.7) makes sure that the capacity of the installed DERs meets the annual peak load. This constraint is necessary for the self-sustainable operation of the port microgrid as a continually used asset. Constraint (4.3.8) states that the variables associated with the installation status of the DERs are binary.

The aim of the operation subproblem on the second stage is to maximize the SPI, which is a convex combination of the four sub-indices defined in Section III.B. However, determining the weight parameters paired with each sub-index is beyond the scope of this paper. In fact, the customizable nature of a microgrid suggests that different priority goals can always be addressed with unique solutions. Therefore, Goal Programming is used in the model formulation to eliminate the need for explicitly specifying the weight parameters. Thus, the objective becomes maximizing multiple goals, which are SOI, SEgI, SEnI, and SSSI (4.3.9). In the goal programming, when the goals follow a dominance order, the goal with the highest dominance has to be optimized first. For instance, if there are N goals that follow a dominance order, i.e., goal n should be optimized first, before considering goal m where $n < m$, then we can implement a sequential algorithm (Fig. 4.2). When the desired values for the goals are known beforehand, this particular model is named Lexicographic [74]. As previously explained, the maximum value for each of the indices (i.e., goals) is known to be 1. Hence, Lexicographic Goal Programming is deemed appropriate for our problem.

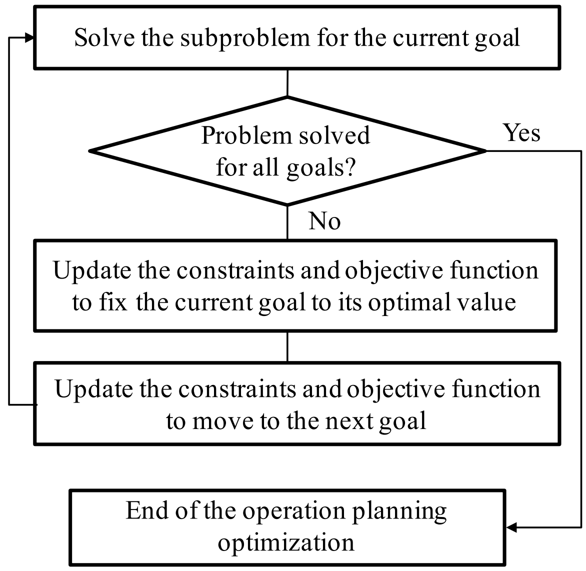


Figure 4.2: Lexicographic Goal Programming for operation planning subproblem

SP objective function given $\bar{x}_i$ (i.e., outputs of the first stage) and for scenario $\omega \in \Omega$ is provided in Equation (4.3.9) as

$$Q_\omega(\bar{x}_i) = \max_{x,P,LS}[SOI_\omega, SEgI_\omega, SEnI_\omega, SSSI_\omega]. \tag{4.3.9}$$

Budget constraint ensures that total investment cost and operation cost does not exceed the available budget (4.3.10). The investment cost of generating units (dispatchable and nondispatchable) depends on their generating capacity. The investment cost of energy storage systems is based on the rated power and rated energy storage capacity. The total operation cost includes: 1) generation cost of dispatchable units, 2) the cost of energy purchase from the main grid, 3) revenue from selling power to the main grid, and 4) the cost of unserved energy. It is assumed that the generation cost of nondispatchable units and energy storage systems are zero due to their renewable nature. The total cost is calculated in the form of present-worth value and incorporates the discount rates. The discount rate refers to the interest rate used to determine the present value and deals with the effect of time on the worth of the money [138]. Budget constraint is

$$\begin{aligned}
&\sum_{t}\sum_{i\in G,W}\kappa_t CC_{it}P_i^{max}\hat{x}_i \\
&+\sum_{t}\sum_{i\in S}\kappa_t(CP_{it}P_i^{max}+CE_{it}C_i^{max})\hat{x}_i \\
&+\sum_{b}\sum_{h}\sum_{t}\sum_{i\in G}\kappa_t c_i P_{ibht,\omega} \\
&+\sum_{b}\sum_{h}\sum_{t}\kappa_t\rho_{bht}(P^{+}_{M,bht,\omega}-P^{-}_{M,bht,\omega}) \\
&+\sum_{b}\sum_{h}\sum_{t}\kappa_t(\upsilon^{H}_{bht}LS^{H}_{bht,\omega}+\upsilon^{L}_{bht}LS^{L}_{bht,\omega})\leq B.
\end{aligned} \tag{4.3.10}$$

Constraints (4.3.11)-(4.3.13)

$$\begin{aligned}
&\sum_{i\in G,W}P^{V}_{ibht,\omega}+\sum_{i\in S}(P^{dch,V}_{ibht,\omega}-P^{ch,V}_{ibht,\omega}) \\
&+P^{V,+}_{M,bht,\omega}-\ P^{V,-}_{M,bht,\omega}=D^{V}_{bht}\quad\forall b,h,t,
\end{aligned} \tag{4.3.11}$$

$$\begin{aligned}
&\sum_{i\in G,W}P^{H}_{ibht,\omega}+\sum_{i\in S}(P^{dch,H}_{ibht,\omega}-P^{ch,H}_{ibht,\omega}) \\
&+P^{H,+}_{M,bht,\omega}-\ P^{H,-}_{M,bht,\omega}+LS^{H}_{bht,\omega}=D^{H}_{bht}\quad\forall b,h,t,\text{ and}
\end{aligned} \tag{4.3.12}$$

$$\begin{aligned}
&\sum_{i\in G,W}P^{L}_{ibht,\omega}+\sum_{i\in S}(P^{dch,L}_{ibht,\omega}-P^{ch,L}_{ibht,\omega}) \\
&+P^{L,+}_{M,bht,\omega}-\ P^{L,-}_{M,bht,\omega}+LS^{L}_{bht,\omega}=D^{L}_{bht}\quad\forall b,h,t
\end{aligned} \tag{4.3.13}$$

create the hourly power balance for critical, high priority, and low priority loads. The hourly load demand can be either satisfied by power generation from the DERs or through power purchased from the main grid. Storage units can be both charged or discharged during each time slot, but the net discharged quantity counts toward demand satisfaction. The microgrid can either buy power from ($P^{+}_{M,bht,\omega}$) or sell power to ($P^{-}_{M,bht,\omega}$) the main grid. There is also the option to partially or totally curtail high priority and low priority loads to assure that power balance is always valid.

Equations (4.3.14) and (4.3.15)

$$P^{-}_{M,bht,\omega} \leq P^{max}_{M} \qquad \forall b,h,t, \text{and} \tag{4.3.14}$$

$$P^{+}_{M,bht,\omega} \leq P^{max}_{M} \qquad \forall b,h,t \tag{4.3.15}$$

control the flow limit between the microgrid and the main grid. The microgrid could benefit from generating power at peak hours to supply local loads and sell the excess power to the main grid at an appropriate price.

The dispatchable units generation capacity and forecasts for nondispatchable units generation are captured by Equations (4.3.16) and (4.3.17) as

$$P_{ibht,\omega} \leq P^{max}_{i}\bar{x}_i \qquad \forall i \in G, \forall b,h,t, \text{and} \tag{4.3.16}$$

$$P_{ibht,\omega} = P^{max}_{i}\bar{x}_i \qquad \forall i \in W, \forall b,h,t. \tag{4.3.17}$$

The charging (4.3.18) and discharging (4.3.19) limits of storage units, and the available stored energy at each hour (charged amount minus discharged amount considering the efficiency rate) (4.3.20) are also considered in

$$P^{ch}_{ibht,\omega} \leq P^{ch,max}_{i}\bar{x}_i \qquad \forall i \in S, \forall b,h,t, \tag{4.3.18}$$

$$P^{dch}_{ibht,\omega} \leq P^{dch,max}_{i}\bar{x}_i \qquad \forall i \in S, \forall b,h,t, \text{and} \tag{4.3.19}$$

$$0 \leq \sum_{k \leq b}(P^{ch}_{ikht,\omega} - \frac{P^{dch}_{ikht,\omega}}{\eta_i}) \leq C^{max}_{i}\bar{x}_i \qquad \forall i \in S, \forall b,h,t. \tag{4.3.20}$$

The main benefit of the storage units is that they compensate for the variation associated with the renewable power generation. Also, the energy storage system could be charged at low price hours and discharged at high price hours. This assists in revenue generation and cost reduction.

Constraints (4.3.21)-(4.3.24) establish the relation between the binary variables for DERs installation status and the continuous variables for DERs power generation. These equations include

$$\hat{x}_i \leq K \sum_b \sum_h \sum_t P_{ibht,\omega} \qquad \forall i \in G, \tag{4.3.21}$$

$$\hat{x}_i \leq K \sum_b \sum_h \sum_t P_{ibht,\omega} \qquad \forall i \in W, \tag{4.3.22}$$

$$\hat{x}_i \leq K \sum_b \sum_h \sum_t P^{ch}_{ibht,\omega} \qquad \forall i \in S, \text{and} \tag{4.3.23}$$

$$\hat{x}_i \leq K \sum_b \sum_h \sum_t P^{dch}_{ibht,\omega} \qquad \forall i \in S. \tag{4.3.24}$$

Constraint (4.3.25) and (4.3.26) limit the curtailed load for each type of load as in

$$LS^H_{bht,\omega} \leq \lambda^H D^H_{bht} \qquad \forall b, h, t, \text{and} \tag{4.3.25}$$

$$LS^L_{bht,\omega} \leq \lambda^L D^L_{bht} \qquad \forall b, h, t. \tag{4.3.26}$$

Equations (4.3.27) to (4.3.38) specify the range of the variables as

$$P_{ibht,\omega} \geq 0 \qquad \forall i \in G, W, \forall b, h, t, \tag{4.3.27}$$

$$P^{ch}_{ibht,\omega} \geq 0 \qquad \forall i \in S, \forall b, h, t, \tag{4.3.28}$$

$$P^{dch}_{ibht,\omega} \geq 0 \qquad \forall i \in S, \forall b, h, t, \tag{4.3.29}$$

$$P^{+}_{M,bht,\omega} \geq 0 \qquad \forall b, h, t, \tag{4.3.30}$$

$$P^{-}_{M,bht,\omega} \geq 0 \qquad \forall b, h, t, \tag{4.3.31}$$

$$LS_{bht,\omega} \geq 0 \qquad \forall b, h, t, \tag{4.3.32}$$

$$P^V_{ibht,\omega}, P^H_{ibht,\omega}, P^L_{ibht,\omega} \geq 0 \quad \forall i \in G, W, \forall b, h, t, \tag{4.3.33}$$

$$P^{ch,V}_{ibht,\omega}, P^{ch,H}_{ibht,\omega}, P^{ch,L}_{ibht,\omega} \geq 0 \qquad \forall i \in S, \forall b, h, t, \tag{4.3.34}$$

$$P^{dch,V}_{ibht,\omega}, P^{dch,H}_{ibht,\omega}, P^{dch,L}_{ibht,\omega} \geq 0 \qquad \forall i \in S, \forall b, h, t, \tag{4.3.35}$$

Table 4.6: Dispatchable units characteristics

Unit No.	Rated Power (MW)	Cost Coefficient ($/MWh)	Annualized Investment Cost ($/MW)
1	5	90	110950
2	5	90	110950
3	3	70	155330
4	3	70	155330
5	2	60	221900
6	2	60	221900

$$P^{V,+}_{M,bht,\omega}, P^{H,+}_{M,bht,\omega}, P^{L,+}_{M,bht,\omega} \geq 0 \qquad \forall b, h, t, \tag{4.3.36}$$

$$P^{V,-}_{M,bht,\omega}, P^{H,-}_{M,bht,\omega}, P^{L,-}_{M,bht,\omega} \geq 0 \qquad \forall b, h, t, \text{ and} \tag{4.3.37}$$

$$LS^{H}_{bht,\omega}, LS^{L}_{bht,\omega} \geq 0 \qquad \forall b, h, t. \tag{4.3.38}$$

4.4 Numerical Results

In this section, we will demonstrate how the proposed framework can be used to identify the best approach to systematically and holistically improve a port's performance through the integration of the microgrid.

As a particular example, we consider the port microgrid planning for the Barbours Cut terminal at the Port of Houston. As the nation's largest export port, the Port of Houston has a 50-mile long ship channel that moves over 8000 ocean-going vessels and 200K barges each year with over $265 Billion in economic activity in Texas and more than 617 Billion nationwide. As the main deepwater container terminal in the Port of Houston, Barbours Cut is one of the world's busiest ports by cargo tonnage and currently going through the modernization program to increase cargo handling efficiency and capacity. In this paper, we are evaluating the implementation of a microgrid which can support the transformation of Barbours Cut into an all-electric terminal to fulfill the port responsibilities for its public and private partners while achieving the goal of zero emission (Figure 4.3).

We consider the planning horizon to be ten years. Model inputs corresponding to the DERs

Figure 4.3: Future Barbours Cut terminal equipped with microgrid and electric facilities

Table 4.7: Nondispatchable units characteristics

Unit No.	Rated Power (MW)	Cost Coefficient ($/MWh)	Annualized Investment Cost ($/MW)
1	2	0	266280
2	2	0	399419

Table 4.8: Storage units characteristics

Unit No.	Rated Power (MW)	Rated Energy (MW)	Annualized Investment Cost-Power ($/MW)	Annualized Investment Cost-Energy ($/MW)
1	1	6	133140	66570
2	2	6	66570	66570
3	3	6	44380	66570

are given in Tables 5.2 and 5.3 and energy storage efficiency (η) is considered to be 90% for all the storage units [139]. The base year peak load is 20 MW, and this peak demand increases by

0.5 MW each year. Load demand varies in the range of [10,24.5] throughout the day [140]. The fraction of critical loads, high priority loads, and low priority loads is set at 30%, 60%, and 10% of the total power demand, respectively. We assume that clean and green sources of energy are not significantly included in the utility grid power supply (i.e., $RS_M = 0$). The coefficient of present-worth value for the first year (κ_1) is 1.02, and for the rest of the years, it is calculated based on the first year value (i.e., $\kappa_t = 1/(1+\kappa_1)^{t-1}$). Market price ($\rho$) fluctuates in the range of [9.87,103.91] ($/MWh) [141]. Parameters associated with SPI calculations such as emission production of the main grid per provided power (EM_M), safety and security incidents per unit of lost power (SSI), energy consumption of the main grid from renewable sources (RS_M) are gathered from the Port of Houston annual reports ([142], [143]). The weight coefficients for SPI calculation based on the four sub-indices are considered to be equal (i.e., $weights = 0.25$). Note that SPI calculation itself is performed only for comparing the results and it is not involved in the optimization model.

Normal probability distribution functions and historical data are used to generate random values for the renewable generation forecasts ([144], [145], [146]) and probability of power outage ([147], [148]) at each time slot. 25 scenarios are generated for each uncertain parameter using Latin Hypercube Sampling to represent the uncertainties ([149], [150]). Scenario reduction is applied to reduce the computation efforts while maintaining the solution accuracy using the GAMS SCENRED tool [80]. Hence, the initially generated 15625 scenarios were reduced to 25 scenarios using SCENRED.

Model (5.2.2)-(5.2.29) has been implemented in GAMS [151] and solved by CPLEX 12.6.1.0 [67] on a Linux server with 128 GB of RAM and 24 processors at 2.53 GHz.

Three case studies are designed to study the model performance:

Case 1) Base Case: Planning without microgrid installation

Case 2) Minimum Cost Model: Microgrid planning with the objective of minimizing the cost

Case 3) Maximum SPI Model: Microgrid planning with the objective of maximizing the SPI sub-indices

Tables 4.9 and 5.4 present the experiment results including the SPI and SPI sub-indices and detailed information for each case.

4.4.1 Base Case

As the performance benchmark, the base design case is developed to determine the optimal strategy for the port entity to meet the terminal's power demand through purchasing power from the main grid and performing hourly load shedding at a minimum cost. This case can be viewed as the traditional approach of terminal operation planning without microgrid integration, and the terminal only has a small backup generator (i.e., rated power = 0.5 MW, cost coefficient = 60 \$/MWh, annualized investment cost = 55475 \$/MW) for supporting critical loads when power is not available from the main grid. We assume that with no installation of microgrids, no DERs are deployed in the invest master problem. Thus, the operation subproblem is to find the minimum cost of supplying loads relying on the main grid for the planning horizon. In this case, the port is not able to fully distinguish and control different load types. Hence, decision variables in the model are not determined for each load type. To calculate the sub-indices without having the load-specific variables, we estimate variables for each load type by considering the associated demand ratios (0.3, 0.6, and 0.1 for critical, high priority, and low priority loads).

Additionally, Equations (4.3.11)-(4.3.13) will be merged into Equation (4.4.1) as

$$\begin{aligned}&\sum_{i\in G,W} P_{ibht,\omega} + \sum_{i\in S}(P^{dch}_{ibht,\omega} - P^{ch}_{ibht,\omega})\\ &+ P^{+}_{M,bht,\omega} - P^{-}_{M,bht,\omega}\\ &+ LS_{bht,\omega} = D_{bht} \quad \forall b,h,t. \end{aligned} \tag{4.4.1}$$

The results in Tables 4.9 and 5.4 indicate that the total cost of this case is 72.1556 million dollars, and the resulted SPI is 0.50. A total amount of 18480 MW power is saved (LS^{L}_{T}) which is the lowest compared in all three cases. Under the assumption that the penetration of clean and green sources of energy in the main grid is negligible, relying on the power supply from the main grid results in a low SEgI (0.06). Meanwhile, SOI is maintained at a relatively high level (0.84) due to the high cost associated with the curtailment of high priority loads and the setting of an upper bound for load shedding. SSSI is also high (0.95) due to the existence of the backup generator. With

Table 4.9: Comparison of indices

Case	SOI	SEgI	SEnI	SSSI	**SPI**
1) Base case	0.84	0.06	0.141	0.95	**0.50**
2) Minimum cost model	0.87	0.19	0.58	0.98	**0.66**
3) Maximum SPI model	0.99	0.50	0.81	1	**0.82**

Table 4.10: Comparison of Results for Three Cases

	Case 1	Case 2	Case 3
Cost ($ million)	72.1556	103.3447	137.7110
LS_T^L (MW of saved power)	18480	114480	131184
q_T (# of TEUs)	16397830	16983460	19326000
CO_{2T} (kilotons)	7882.646	6676.235	3063.924
RS_T (MW)	0	174600	732691
SSI_T	6	2	0
$P_{M,T}^+$ (MW)	1127026	888078	0
$P_{M,T}^-$ (MW)	0	36491	354

no renewable sources used in this case, the CO_2 emission level is at a high quantity of 7882.646 kilotons. No power is sold back to the main grid (i.e., $P_{M,T}^- = 0$). The expected saved power by curtailing low priority loads is 18480 MW.

4.4.2 Minimum Cost Model

This case presents the conventional approach to microgrid planning with the objective of cost minimization. The objective function of the master problem is the investment cost (i.e., the first two terms in Equation (4.3.10)) plus the expected operation cost as defined in

$$\begin{aligned}\min_{x_i} &\sum_t \sum_{i \in G,W} \kappa_t CC_{it} P_i^{max} x_i \\ &+ \sum_t \sum_{i \in S} \kappa_t (CP_{it} P_i^{max} + CE_{it} C_i^{max}) x_i \\ &+ E_\omega [Q'_\omega(x_i)]. \end{aligned} \tag{4.4.2}$$

The latter is obtained by the optimality cuts that are added to the master problem. The constraints of the investment master problem include Equations (4.3.7) and (4.3.8). The objective function of the operation subproblem is the operation cost. Therefore, the budget constraint, as described in Equation (4.3.10), is removed from the set of subproblem constraints. Results obtained from this case indicate that DERs with lowest overall cost (i.e., 5 dispatchable units (units 1, 2, 3, 4, and 6), 1 nondispatchable unit (unit 1), and 2 storage units (units 1 and 3)) are installed to satisfy the annual peak load constraint as described in Equation (4.3.7). However, the energy is purchased from the main grid, or the power demand is curtailed whenever the cost of doing such is lower than the cost of the DER on-site generation. We observe that the total cost, in this case, is 103.3447 million dollars. With the installation of renewable DERs, there is an improvement in the energy and environment portion compared with Case 1. However, it is evident that a cost-driven planning approach leads to limited improvement in SPI as it does not fully capture the unique nature and operation characteristics of a port.

4.4.3 Maximum SPI Model

In this case, we solve the model presented in Equations (4.3.6) through (4.3.38). This model incorporates all the performance metrics of operational, environmental, energy-related, and safety and security aspects of the port activities as identified and modeled in Section II.C with a pre-specified budget constraint (4.3.10). For the preemptive goal programming, we consider that the following dominance order exists in terms of the priorities: SOI ≥ SEgI ≥ SEnI ≥ SSSI. The results of this case study indicate that 4 dispatchable units (units 1, 2, 3, and 4), 1 nondispatchable unit (unit 2), and 3 storage units are installed. The highest index value among the three cases analyzed is obtained with the SPI equal to 0.82. SOI is equal to 0.99, and SSSI is 1, which is its maximum potential quantity. This suggests that the generation capacity is always able to meet almost all of the load demand within the terminal to facilitate the throughput and no security-related incidents occur due to the continuity of the power supply (i.e., $SSI = 0$). SEgI has been enhanced noticeably from 0.19 from Case 2 to 0.50 in Case 3, and SEnI is also increased to 0.81. 732691 (MW) of power is provided through renewable sources, which is 4.20 times the renewable generation decided by the minimum cost model. CO_2 emission is reduced by 54% compared to the minimum cost model and 61% compared to the base case. It can also be observed that while the microgrid still benefits from trading its excessive power back to the main grid, the total power sold to the main grid (P_M^-) in Case 3 is less than Case 2 which is completely cost-driven.

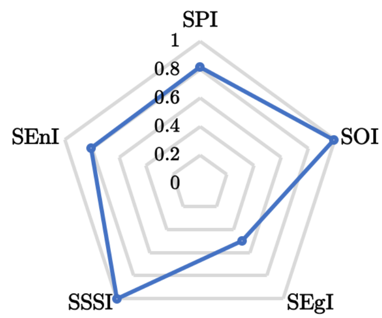


Figure 4.4: Index Values-Order Set$_1$

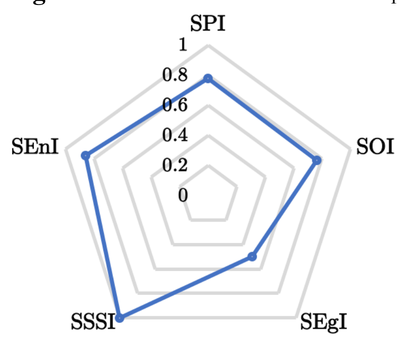


Figure 4.5: Index Values-Order Set$_2$

To analyze the model behavior with different orders of the goals, we have considered four order sets. The sub-indices and their associated priorities are the elements of the sets: Set$_1$ = {(SOI,1), (SEgI,2), (SEnI,3), (SSSI, 4)}, Set$_2$ = {(SOI,3), (SEgI,1), (SEnI,2), (SSSI, 4)}, Set$_3$ = {(SOI,2), (SEgI,3), (SEnI,1), (SSSI, 4)}, and Set$_4$ = {(SOI,4), (SEgI,3), (SEnI,2), (SSSI, 1)}. Lower numbers correspond to higher priorities. In each set, a different sub-index has the highest priority. Figures 4.4, 4.5, 4.6, 4.7 present the index and sub-index values associated with Set$_1$, Set$_2$, Set$_3$, Set$_4$, respectively.

Figure 3 indicates that the highest SPI (i.e., SPI = 0.82) can be achieved with Set$_1$, while the lowest SPI (i.e., SPI = 0.75) is associated with Set$_4$. SOI is at its peak value (i.e., SOI = 0.99) with

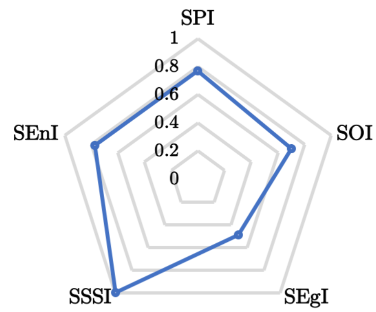


Figure 4.6: Index Values-Order Set_3

Figure 4.7: Index Values-Order Set_4

Set_1, which is expected because SOI has the highest priority in this set. In Set_2, SEgI is the most important goal and is increased to 0.50 (Figure 4.5). Similarly, SEnI is increased to 0.88 when it has the highest priority (Figure 4.6). SSSI is given the highest priority in Set 4; however, it has reached its maximum level of 1 with all of the sets.

The results of the analysis suggest that the overall terminal performance is improved most for Set_1 in which the main goal is to increase reliability through the microgrid integration by assuring the continuity and the availability of the power supply.

4.5 Conclusion

While the economic and environmental viability of microgrids has been well discussed in the literature, ports remain a relatively unexplored segment for microgrid adoption. In this work, we have attempted to fill this gap by evaluating the benefits of microgrid integration and how these advantages can be translated into opportunities for the port industry in particular. Our research findings provide an initial assessment on how to transform a traditional industrialized port into a contributing component of a sustainable eco-system through the use of microgrids. In particular, we have implemented a set of metrics from different key operation domains to facilitate the formation of a holistic approach for planning port microgrids. Case studies and simulation results highlight, in a quantitative way, that through the proposed planning approach, the microgrid can contribute to various aspects of port operation and management such as avoiding facility downtime, improved power quality, cost savings, energy dependency, and emission reduction.

Chapter 5

Co-Optimization of Onshore Power Supply and Port Microgrid Under Uncertainty

5.1 Introduction

One of the key challenges of recent policy-making in the context of transportation is boosting a sustainable transportation system, with the principal goal of preventing its adverse effects on the environment and health [48]. As ports are key components of maritime transportation networks, the environmental impact of their operations and development has been the concern of many researchers recently. Air pollution is one of the main environmental effects of port activities, and it is a leading factor of both climate change and severe health issues [9]. Approximately 230 million people are directly exposed to the emissions in the top 100 world ports and most air pollutants in ports (CH_4, CO, CO_2 and NO_x) are estimated to quadruple by 2050, which means 70 million tonnes of CO_2 and 1.3 million tonnes of NO_x from shipping emissions in ports by 2050 [152]. Air emission health effects directly impact the residents of the local community surrounding ports. These health impacts include asthma, cardiovascular disease, lung cancer, bronchitis symptoms, premature births, and premature mortality [1]. The greenhouse gases (GHGs) in the emission are also considered the leading cause of climate change that is associated with natural disasters, environmental deterioration, and threats for human health and safety [153, 127].

Recent studies have demonstrated that fuel burn in the ship's combustion engine is the most significant contributor to the port air emissions. Studies have estimated that ocean-going ships produce at least 15% of the world's NO_x (more than all of the world's cars, busses and trucks combined), between 2%-3% of greenhouse gasses, and between 3%-7% of global SO_x output. Without corrective actions, these amounts will potentially double in the next decade [154]. These ships with mentioned potential for emitting pollutions, at berthing, require electricity to support the activities like loading, unloading, heating and lighting, and other on-board activities. Currently, this power is generally provided by vessels auxiliary engines that emit various air pollutants.

As an alternative to the traditional power supply and a solution to the emission problem, vessels can be hooked up to an onshore power supply (OPS). OPS, or cold-ironing, provides power to vessels at the berth through shore-to-ship power cables in which auxiliary engines on-board can be turned off. This power supply ensures that the ship's operations can be performed without any interruption, and air emissions from diesel fuels caused by berthing activities will be reduced noticeably [45]. Currently, many industrial ports around the globe, including Port of Antwerp, Port of Gothenburg, POLA, and Port of Seattle, are testing and moving toward integrating OPS [45] technologies into their terminal electricity distribution systems. In fact, Onshore power supply (OPS) is one of the strategies recommended by the World Port Climate Initiative for reducing the environmental issues caused by vessels berthing at the ports. Despite the evident benefits, currently, only limited ports and vessels are equipped to be capable of utilizing OPS due to the fact that implementing OPS requires a comprehensive study on the port conditions, existing regulations, feasibility of implementation, cost-effectiveness, and optimal quantities and locations for installations.

In this paper, we are aiming to develop a framework for optimizing investment and planning of OPS for the sustainable ports of the future. We envision that the integration of OPS is best accompanied by another prevailing technology: microgrid. A microgrid is a relatively small-scale localized energy network that features an effective integration of high penetration levels of Distributed Energy Resources (DERs), such as renewable energy resources, energy storage devices, and controllable loads [7]. A microgrid can operate both when connected to the utility grid or in the islanding mode. Microgrid can provide a reliable, clean, and controllable power supply [155]. We propose an approach for co-optimization of microgrid and OPS at ports to support green and modern development of ports.

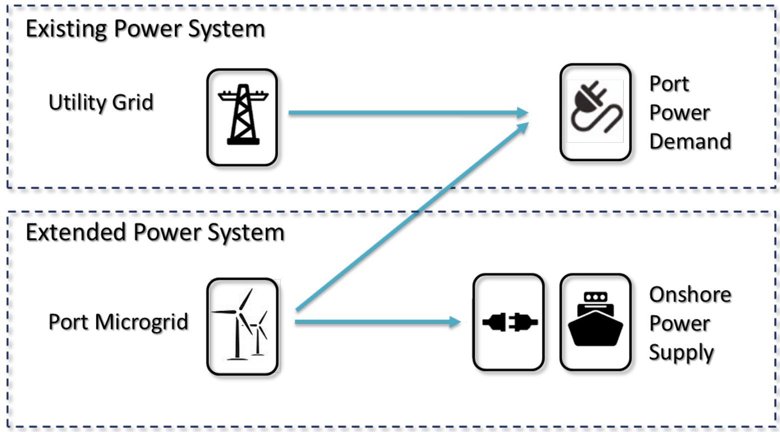


Figure 5.1: Extended power system at port microgrids with integrated OPS

The remainder of this paper is organized as follows. Section II explains the proposed methodology for the co-optimization of the port microgrid and onshore power supply for the vessels at berth. Section III shows the case study of the Barbours Cut terminal at the Port of Houston to illustrate the effectiveness and an example of the implementation of the developed model. Finally, Section IV concludes the paper.

5.2 Methodology

In this work, we aim to model the port microgrid and OPS investment and planning along together to promote sustainable development of the ports. Table 5.1 shows the notation used in developing the optimization model.

Microgrid enables differentiating different types of loads within the port, hence, we divide the port power demand into two types: regular loads (referred to by superscript R) and OPS loads (referred to by superscript O) as follow:

$$D_{hmy} = D^{R}_{hmy} + \sum_{j \in V} D^{O}_{jhmy} \quad \forall h, m, y. \tag{5.2.1}$$

Regular loads in ports are the power demand for lighting, monitoring systems, buildings, offices,

Table 5.1: Nomenclature

G	Set of dispatchable units
W	Set of nondispatchable units
S	Set of energy storage systems
V	Set of candidate stations for implementing onshore power supply
Ω	Set of scenarios
y	Index for year
m	Index for month
h	Index for hour
i	Index for DERs
j	Index for OPS candidate station
ch	Superscript for energy storage charging mode
dch	Superscript for energy storage discharging mode
ω	Index for scenarios
R	Superscript for regular load
O	Superscript for OPS load
c	Generation price for dispatchable units
c_A	Generation price for the auxiliary engine of the vessels at berth
CC	Annualized investment cost of generating units
CP	Annualized investment cost of storage - energy
CE	Annualized investment cost of storage - power
CV	Annualized investment cost of OPS units
C^{max}	Rated capacity of energy storage systems
D	Load demand
D^{max}	Annual peak load
K	Large positive constant
P_i^{max}	Rated power of DERs
P_j^{max}	Power flow capacity of OPS stations
P_M^{max}	Flow limit between microgrid and the main grid
κ	Coefficient of present-worth value
ρ	Market price
υ	Value of lost load (VOLL)
η	Energy storage efficiency
λ	Maximum allowable load shedding (% of load)
Pr_M^{Outage}	Probability of main grid power outage
EM	Emission production
B	Budget
COL	Cost of load shedding
$\underline{z}$	Lower bound for number of stations that should be equipped with OPS
$\bar{z}$	Upper bound for number of stations that should be equipped with OPS
x	DER investment state
z	OPS station investment state
P	DER output power
P_M^+	Power bought from main grid
P_M^-	Power sold to main grid
P_A	Power generation from auxiliary engine of the vessels at berth
LS	load shedding

and other common electric equipment within the port. OPS load includes the power demand for vessels at berth. As for the inherent uncertainties of microgrid planning, renewable energy resources such as wind and solar energy are incorporated in microgrids, and power generation from these sources is associated with uncertainty [136]. In this work, we also consider the uncertainty related to the probability of disruptions and power outage in the main grid.

To obtain the optimal investment and planning decisions for the port microgrid and the OPS with the goal of minimizing emission level at the port, we propose a two-stage stochastic optimization model which includes the investment master problem and operation subproblem. In the first stage, the investment master problem is an integer programming model, and in the second stage, the operation planning subproblem is a linear programming model. The investment problem obtains the optimal installation status of the DERs in the microgrid and the optimal OPS installation for the terminal stations. The operation planning subproblem decides on the optimal power planning for OPS and the auxiliary engines of the vessels, as well as the optimal generation mix of the DERs, load shedding, and hourly flow between the microgrid and main grid. Benders Decomposition is implemented to solve the problem. Note that in the formulation below, wherever superscripts R and O or omitted, it means that the related variable or parameter refers to the aggregated value for both load types.

The investment master problem is provided below and this master problem obtains the optimal installation mix of DERs as well as the stations that should be equipped with OPS as in

$$\min_{x,z} \quad E_{\omega}[Q_{\omega}(x_i)], \tag{5.2.2}$$

$$s.t. \quad D_y^{max} + \sum_{j \in V} P_j^{max} z_j \leq \sum_{i \in G,W,S} P_i^{max} x_i \quad \forall y, \tag{5.2.3}$$

$$\underline{z} \leq \sum_{j \in V} z_j \leq \bar{z}, \text{ and} \tag{5.2.4}$$

$$x_i, z_j \in \{0, 1\}, \quad i \in G, W, S, j \in V. \tag{5.2.5}$$

The objective of the master problem is to minimize the expected value of the Q_{ω} over the scenarios (5.2.2), which refers to the subproblem objective function and will be determined by the optimality cuts. Constraint (5.2.3) states that a sufficient number of DERs should be installed in order to meet the annual peak demand and the OPS power demand for the vessels at berth. This constraint is needed for the islanding capability of the microgrid. Constraint (5.2.4) ensures that the number of stations that are equipped with OPS is within the required bounds. Constraint (5.2.5) states that the variables associated with the installation status of the DERs are binary.

The aim of the operation subproblem on the second stage is to minimize the emission level at the port. Each power source has an emission rate per provided power, and the total amount of the emission equals the summation of emission from the existing power sources. The final emission level at the port after integrating microgrid and OPS is calculated by

$$\begin{aligned} EM^T \quad = \quad & \sum_h \sum_m \sum_y \sum_{i \in G,W} \Big(EM_i P_{ihmy} \\ & + EM_M (1 - Pr^{Outage}_{M,hmy}) P^+_{M,hmy} \Big) \\ & + \sum_{j \in V} EM_A P_{A,jhmy}. \end{aligned} \tag{5.2.6}$$

The objective function of the subproblem given $\hat{x}_i, \hat{z}_i$ (i.e., outputs of the first stage) and for scenario $\omega \in \Omega$ is provided in

$$Q_\omega(\bar{x}_i) = \min_{x,z,P,LS} EM^T_\omega. \tag{5.2.7}$$

Budget constraint makes sure that total investment cost and operation cost is less than the budget (5.2.8). The first three terms in the budget constraint are related to the investment cost of the DERs in the microgrid and OPS for each vessel station. The rest of the terms reflect the total operation cost which consists of: 1) generation cost of dispatchable units, 2) the cost of energy purchase from the main grid, 3) revenue from selling power to the main grid, 4) the cost of load shedding, and 5) the cost of power generation from the auxiliary engines for the vessels at berth. Nondispatchable units and energy storage systems have a generation cost of zero. The net present value of the total cost is calculated by including the discount rates [138] in

$$\begin{aligned}
&\sum_{y}\sum_{i\in G,W}\kappa_y CC_{iy}P_i^{max}\hat{x}_i \\
&+\sum_{y}\sum_{i\in S}\kappa_y(CP_{iy}P_i^{max}+CE_{iy}C_i^{max})\hat{x}_i \\
&+\sum_{y}\sum_{j\in V}\kappa_y CV_{jy}P_j^{max}\hat{z}_j \\
&+\sum_{h}\sum_{m}\sum_{y}\sum_{i\in G}\kappa_y c_i P_{ihmy,\omega} \\
&+\sum_{h}\sum_{m}\sum_{y}\kappa_y\rho_{hmy}(P^{+}_{M,hmy,\omega}-P^{-}_{M,hmy,\omega}) \\
&+\sum_{h}\sum_{m}\sum_{y}\kappa_y(\upsilon^{R}_{hmy}LS^{R}_{hmy,\omega}+\upsilon^{O}_{hmy}LS^{O}_{hmy,\omega}) \\
&+\sum_{h}\sum_{m}\sum_{y}\sum_{j}\kappa_y c_A P_{A,jhmy,\omega}\leq B. \qquad (5.2.8)
\end{aligned}$$

Constraints (5.2.9)-(5.2.10),

$$\begin{aligned}
&\sum_{i\in G,W}P^{R}_{ihmy,\omega}+\sum_{i\in S}(P^{dch,R}_{ihmy,\omega}-P^{ch,R}_{ihmy,\omega}) \\
&+\ P^{R,+}_{M,hmy,\omega}-\ P^{R,-}_{M,hmy,\omega}+LS^{R}_{hmy,\omega} \\
&=\ D^{R}_{hmy}\quad \forall h,m,y,\text{ and} \qquad (5.2.9)
\end{aligned}$$

$$\begin{aligned}
&\sum_{i\in G,W}P^{O}_{ijhmy,\omega}+\sum_{i\in S}(P^{dch,O}_{ijhmy,\omega}-P^{ch,O}_{ijhmy,\omega}) \\
&+\ P^{O,+}_{M,jhmy,\omega}-\ P^{O,-}_{M,jhmy,\omega}+LS^{O}_{jhmy,\omega}+P_{A,jhmy,\omega} \\
&=\ D^{O}_{jhmy}\quad \forall j\in V,\forall h,m,y \qquad (5.2.10)
\end{aligned}$$

ensure the hourly power balance for regular and OPS loads. The regular load can be satisfied by power generation from the DERs, power bought from the main grid, and the power discharged from the storage units. The power demand at berth can be provided by the microgrid, the main grid, or the auxiliary engine of the vessels. For both types of loads, there is the option to curtail the load considering a value of lost load cost.

Equations (5.2.11) and (5.2.12) force the bounds for the flow between the microgrid and the main grid. The dispatchable units generation capacity and forecasts for nondispatchable units generation are shown by Equations (5.2.13) and (5.2.14). These equations include

$$P^{-}_{M,hmy,\omega} \leq P^{max}_{M} \qquad \forall h, m, y, \tag{5.2.11}$$

$$P^{+}_{M,hmy,\omega} \leq P^{max}_{M} \qquad \forall h, m, y, \tag{5.2.12}$$

$$P_{ihmy,\omega} \leq P^{max}_{i} \hat{x}_i \qquad \forall i \in G, \forall h, m, y, \text{and} \tag{5.2.13}$$

$$P_{ihmy,\omega} = P^{max}_{i} \hat{x}_i \qquad \forall i \in W, \forall h, m, y. \tag{5.2.14}$$

Constraints (5.2.15), (5.2.16), (5.2.17), (5.2.18) model the charging and discharging limits of the storage units as well as the available stored energy at each hour as in

$$P^{ch}_{ihmy,\omega} \leq P^{ch,max}_{i} \hat{x}_i \qquad \forall i \in S, \forall h, m, y, \tag{5.2.15}$$

$$P^{dch}_{ihmy,\omega} \leq P^{dch,max}_{i} \hat{x}_i \qquad \forall i \in S, \forall h, m, y, \tag{5.2.16}$$

$$0 \leq \sum_{k \leq h} (P^{ch}_{ikmy,\omega} - \frac{P^{dch}_{ikmy,\omega}}{\eta_i}) \qquad \forall i \in S, \forall h, m, y, \text{and} \tag{5.2.17}$$

$$\sum_{k \leq h} (P^{ch}_{ikmy,\omega} - \frac{P^{dch}_{ikmy,\omega}}{\eta_i}) \leq C^{max}_{i} \hat{x}_i \qquad \forall i \in S, \forall h, m, y. \tag{5.2.18}$$

Load for vessels at berth should be either satisfied by the OPS station (5.2.19) or the auxiliary engines of the vessels (5.2.20). Constraint (5.2.21) and (5.2.22) limit the curtailed load for each type of load. These equations include

$$\begin{aligned} &D^{O}_{jhmy} - LS^{O}_{jhmy,\omega} - P_{A,jhmy,\omega} \\ &\leq P^{max}_{j} \hat{z}_j \qquad \forall j \in V, \forall h, m, y, \end{aligned} \tag{5.2.19}$$

$$P_{A,jhmy,\omega} \leq D^O_{jhmy} \qquad \forall j \in V \forall h, m, y, \quad (5.2.20)$$

$$LS^R_{hmy,\omega} \leq \lambda^R D^R_{hmy} \qquad \forall h, m, y, \text{and} \quad (5.2.21)$$

$$LS^O_{hmy,\omega} \leq \lambda^O D^O_{hmy} \qquad \forall h, m, y. \quad (5.2.22)$$

Equations

$$P^R_{ihmy,\omega}, P^O_{ihmy,\omega} \geq 0 \qquad \forall i \in G, W, \forall h, m, y, \quad (5.2.23)$$

$$P^{ch,R}_{ihmy,\omega}, P^{ch,O}_{ihmy,\omega} \geq 0 \qquad \forall i \in S, \forall h, m, y, \quad (5.2.24)$$

$$P^{dch,R}_{ihmy,\omega}, P^{dch,O}_{ihmy,\omega} \geq 0 \qquad \forall i \in S, \forall h, m, y, \quad (5.2.25)$$

$$P^{R,+}_{M,hmy,\omega}, P^{O,+}_{M,hmy,\omega} \geq 0 \qquad \forall h, m, y, \quad (5.2.26)$$

$$P^{R,-}_{M,hmy,\omega}, P^{O,-}_{M,hmy,\omega} \geq 0 \qquad \forall h, m, y, \quad (5.2.27)$$

$$LS^R_{hmy,\omega}, LS^O_{hmy,\omega} \geq 0 \qquad \forall h, m, y, \text{and} \quad (5.2.28)$$

$$P_{A,jhmy,\omega} \geq 0 \qquad \forall j \in V, \forall h, m, y \quad (5.2.29)$$

show the range of the continuous variables in the subproblem.

5.3 Case Study and Preliminary Results

In this section, we show how the proposed approach can optimize the investment and planning of OPS for the port microgrids. In particular, we consider the port microgrid planning along with the OPS planning for the Barbours Cut terminal at the Port of Houston. We evaluate the implementation of a microgrid and OPS, which together can mitigate emission levels from the vessels at berth.

The planning horizon is considered to be ten years. Parameters related to the DERs are provided in Tables 5.2 and 5.3 and energy storage efficiency (η) is 90% for the storage units [139]. The first year peak load is 20 MW, and this peak demand increases by 0.5 MW each year. Load demand takes values in the range of [10,24.5] in MW each day [140]. The coefficient of present-worth value for the first year (κ_1) is 1.02 ($\kappa_y = 1/(1+\kappa_1)^{y-1} \quad \forall y > 1$). Market price ($\rho$) varies in the range

Table 5.2: Dispatchable units characteristics

Unit No.	Rated Power (MW)	Cost Coefficient ($/MWh)	Annualized Investment Cost ($/MW)
1	5	90	110950
2	5	90	110950
3	5	90	110950
4	5	90	110950
5	3	70	155330
6	3	70	155330
7	3	70	155330
8	2	60	221900
9	2	60	221900
10	2	60	221900

Table 5.3: Nondispatchable units characteristics

Unit No.	Rated Power (MW)	Cost Coefficient ($/MWh)	Annualized Investment Cost ($/MW)
1	2	0	266280
2	2	0	399419

Table 5.4: Results for the MG and OPS installation at Barbours Cut Terminal at Port of Houston

Case	EM_T (kilotons of CO_2)	$EM_{Vessels}$ (kilotons of CO_2)	Cost ($ million)	P_{MG} (MW)	P_A (MW)	$p^+_{M,T}$ (MW)	$p^-_{M,T}$ (MW)	LS_T (MW)	RS_T (MW)
1	16336	10502	213.155	0	1,296,000	918,288	0	393,552	0
2	11193	10502	307.582	918,288	1,296,000	0	0	393,552	784,328
3	7168	3588	305.315	2,214,288	0	0	0	393,552	1,048,051

of [9.87,103.91] ($/MWh) [141]. Emission production rates (i.e., EM_M and EM_A) are collected from the Port of Houston annual report [142]. To generate scenarios for the renewable generation forecasts and probability of power outage at each hour, Normal probability distribution functions and historical data are used [144, 145, 147]. Latin Hypercube Sampling and scenario reduction are applied to generate and reduce scenarios [149, 80]. 10 stations are considered as the candidate stations for implementing OPS, five of which have the capacity of 1 MW, and the rest have the capacity of 2 MW. The cost of power generation from the auxiliary engines of the vessels is $90 per MW, and the annualized investment cost for installing OPS at each station is 50000 ($/MW). In the

Table 5.5: Storage units characteristics

Unit No.	Rated Power (MW)	Rated Energy (MW)	Annualized Investment Cost-Power ($/MW)	Annualized Investment Cost-Energy ($/MW)
1	1	6	133140	66570
2	2	6	66570	66570
3	3	6	44380	66570

provided case studies, it is assumed that all of the vessels' power demand should be satisfied and load curtailment is not allowed for them.

Model (5.2.2)-(5.2.29) and the decomposition algorithm have been implemented in GAMS [151] and solved by CPLEX 12.6.1.0 [67] on a Linux server with 384 GB of RAM and 40 Intel Xeon E5-2690 processors (10 cores per socket) at 3.00 GHz. The results for three cases are provided in Table 5.4. Case 1 is the base case which is the performance benchmark and shows the terminal traditional power planning without MG and OPS. Case 2 allows the port authority to install and plan microgrid, however, OPS installation is not an option. In Case 3, both microgrid and OPS are the available options for emission mitigation. The results indicate that in Case 3, all of the 10 dispatchable units and the 2 nondispatchable units are installed to satisfy the demand for the port regular power demand as well as the demand for OPS. 10 stations are equipped with OPS. The total investment and operation cost over the 10-year planning horizon is $3.053 M, which embraces the investment and operation cost both for the microgrid implementation and OPS integration. No storage unit is installed because of the sufficient capacity of the available dispatchable units. 100% of the OPS load is satisfied through power generation from the dispatchable units, and the rest is curtailed when necessary. The emission production related to the vessels at berth reduces by 66%, and the overall emission level of the port decreases from 16336 kilotons of CO_2 to 7168 kilotons, which is about 56% reduction. We observe that the proposed approach is well capable of determining optimal investment and operation planning for the port microgrid and OPS in order to significantly mitigate emission during the desired planning horizon.

5.4 Conclusion

This study develops a holistic optimization framework for providing clean and green energy supply to the ports and ocean-going vessels. We attempted to fill the gap in literature for integrating microgrid and OPS for the ports by optimizing the investment and planning of microgrid along with OPS and evaluating their benefits for the ports and vessels. This work considers the inherent uncertainties associated with microgrid planning and renewable energy generation, and proposes an efficient solution approach for obtaining optimal decisions and insights for the business stakeholders. Case study and simulation results highlight that by the proposed methodology, the port microgrid combined with the OPS can mitigate emission levels at ports significantly and enhance the sustainability of the ports.

Chapter 6

Stimulating Sustainable Energy at Maritime Ports by Hybrid Economic Incentives: A Bilevel Optimization Approach

6.1 Introduction

Maritime transportation accounts for 90% of cross-border world trade, as measured by volume. Ports are considered to be the backbone of this network by connecting value chains and markets in different parts of the world [156]. In 2018, U.S. ports contributed $5.4 trillion to the economy of the country, which accounts for nearly 26% of the nation's $20.5 trillion economic output [157]. As dependence on these ports grows, so does the severity of challenges against them. The main operation of ports is to load and unload vessels and transport the cargo to warehouses and other destinations, which has made maritime ports to be major *energy hubs*. The increasing energy demand for port operations has brought forward urgent issues related to the port industry's substantial impacts on the environment and public health [153]. To satisfy their energy demands, port entities produce a significant amount of environmental pollution through land and sea transportation, waste disposal, and expansion activities [127]. According to the air emission inventory organized by the Port of Los Angeles (POLA) in 2015, the principal sources of airborne emissions at ports are directly linked to the activities of major consumers in the port energy system, such as ocean-going vessels (OGVs), cargo handling equipment (CHE), heavy-duty vehicles (HDVs), harbor crafts, and locomotives [2].

It is reported that approximately 230 million people are directly exposed to emissions originating from the top 100 global container ports. The existence of air pollutants produced by ports is estimated to quadruple by 2050; this equates to approximately 70 million tons of CO_2 and 1.3 million tons of NO_x [158]. Air emissions directly impact the health conditions of residents living in the communities surrounding ports and cause diseases such as asthma, lung cancer, cardiovascular diseases, and premature mortality [**?**]. Meanwhile, greenhouse gases (GHGs) are considered to be the primary contributing factor to climate change and global warming [9]. To address these pressing issues, many port entities and authorities are exploring new decarbonization and emission mitigation solutions to the traditional port energy management paradigm in port energy systems. These proposed solutions will allow for the movement towards a port industry that promotes and facilitates renewable energy, sustainable development, steady economic growth, and better quality of life and social welfare for citizens living in the port neighborhood [127], [155].

Existing port sustainable energy solutions embrace technical, operational, and economic dimensions. The abatement measures for OGVs are classified into four categories: alternative fuels or power sources (e.g., liquefied natural gases (LNG), biofuels, solar and wind energy, and nuclear energy), operational measures (e.g., hull conditioning, propeller conditioning, trim and draft optimization), technical measures (e.g., the machinery of main and auxiliary engines, underwater measures for propeller and hull), and structural changes (e.g., port efficiency, vessel speed reduction, and cold ironing) [159, 160, 161]. Zero-emission electric transport vehicles and cranes are readily deployable to reduce CHE emission [159, 162, 163, 164]. Moreover, alternative fuels, speed optimization, idling reduction, and truck platooning can be adopted for HDVs emission reduction [165, 166, 167]. Alternative fuels, hybrid, and all-electric harbor craft and locomotives are also available to mitigate emissions [168, 169].

Despite the existence of the aforementioned sustainable energy technologies and products, ports and shipping liners are reluctant to initiate them due to the barriers of implementation cost and time. As profit-driven organizations, port entities are constantly challenged by their stakeholders to justify the pursuit of emission-reduction efforts and the investment of sustainable energy solutions in terms of payback, return on investment, and revenue enhancement. To address this issue, the concept of regulations and economic incentives has emerged to promote emission reductions in the ports' energy activities [57]. According to the United States Environmental Protection Agency, three types of instruments are available for policy-makers: i) *mandatory regulations* (command-and-control), ii) *market-based policies*, and iii) *hybrid approaches* (a combination of command-and-control and market-based policies) [10]. Mandatory regulations refer to the traditional mandates and standards which oblige specific limits, technologies, or processes that polluters must adopt to reduce their emission. Market-based policies, used as performance-based standards, rely on market forces to motivate emission reduction by economic means such as incentives and taxes [170]. Regulatory approaches provide certainty in mitigating emission, while market-based policies provide flexibility and willingness to polluters [171] to meet the emission standard. Hybrid approaches combine the certainty and flexibility of these two and hence, are becoming more appealing to policy-makers. However, the design of such policies is not straightforward. Attributes such as operational costs, continuity of operations, regulation compliance, port competitiveness, and regulation attractiveness have to be taken into consideration collectively to form an overall “sensible" solution [58].

The necessity of economic regulations for emission reductions at ports has been discussed in the literature [172], [173]. In particular, the need for pollution taxes was highlighted and revealed through a survey with port operators and government officials in [49]. The results of the survey emphasized the importance of a practical policy-making approach that motivates ports to reduce their emission. The impacts of different environmental policies on air emission mitigation are analyzed in [50]. An important regional characteristic that should be incorporated in the design of an effective economic policy is whether there are multiple ports or one port in the region. A market-based approach for pollution control in a region with multiple ports is studied in [53]. In regards to environmental regulations, the effectiveness of a unilateral maritime emission regulation versus a uniform maritime emission regulation in the presence of multiple ports has been investigated in [54]. The results of this investigation indicated that a unilateral regulation may lead to increased emissions, whereas a uniform regulation always reduces the total emission. The literature has also noted the adoption of bilevel optimization models used to design tax and incentive policies that promote clean energy. In this context, a bilevel optimization model has been developed in [56] to study the renewable incentive design for generation capacity expansion. As another instance, authors in [57] designed a carbon tax scheme based on the production emission factor via bilevel programming. However, the hybrid economic approach remains largely unexplored in the literature for port energy system design and emission mitigation.

In this paper, we propose a novel hybrid economic approach to aid both the regulatory entities (e.g., government agencies, policy-makers) and the polluting entities (e.g., ports entities, shipping liners) to holistically improve the sustainability of a region consisting of multiple ports. The proposed approach allows the regulatory authority to minimize the emission caused by port energy activities through carbon taxes and subsidies in a way that the port customers' (i.e., energy consumers) welfare and competitiveness are not noticeably impaired. More specifically, we propose to formulate the problem as a multi-objective bilevel programming model in which the upper-level provides the optimal set of tax and incentive policies for the regulatory entity as well as emission goal, and the lower-level offers the optimal investment decisions regarding the choice of green and sustainable energy solutions and the setting of port service prices for the port entities. Simulation results verify that the proposed approach is capable of simultaneously satisfying the demands of the regulator, ports, and port customers while providing the first two with optimal policies.

The contributions of this paper are highlighted as follows:

- This paper develops a novel hybrid economic approach to stimulate sustainable energy activities at maritime ports. To our knowledge, this paper is one of the pioneering research efforts that aim to combine the certainty of command-and-control and the flexibility of market-based economic incentives in the unique context of maritime transportation.

- A novel multi-objective bilevel programming model is presented in this paper to enable the co-operation of different stakeholders involved in the design, ownership, operation, and management of port energy systems based on their points of interest as well as the hierarchy and competition among them.

- The simulation results based on actual port data reveal and offer insights into the effectiveness of taxes, incentives, and the combination of the two on mitigating emissions with the consideration of the satisfaction of port energy demand.

The remainder of this paper is organized as follows. The methodology section presents the proposed model and its associated solution methodology. Section III illustrates our approach through numerical examples and performance analysis. Finally, Section IV concludes the paper by highlighting the contributions and results of our study as well as insights for future research.

6.2 Methodology

As set forth above, our problem setting involves two groups of decision-makers: a regulatory authority and competing ports in the associated region. The regulatory authority aims to promote sustainable growth that lowers the combined emission from polluting ports in the region, all while maintaining service availability for the ever-growing energy demand. This is achieved through the establishment of a target emission limit, i.e., an emission cap for each port, to motivate the implementation of sustainable and green energy solutions. The port receives incentives if its emission level is below the cap. Otherwise, the port is penalized by an emission tax. Our approach is hybrid in the sense that it incorporates the certainty of command-and-control by establishing the emission caps while offering economic stimulation to encourage port entities to adopt sustainable energy technologies and meet the assigned emission caps through profitable approaches. The regulatory authority also considers the welfare of the port customers, modeled by the amount of fulfillment of port energy demand. It is noted that in this work, this demand is measured by the total volume of containers handled by the port facility.

The second group of decision-makers is comprised of competing ports in the region that seek to maximize their profits from providing services to port customers (i.e., vessels and ship liners). This profit is impacted by the choice of sustainable energy technologies, the emission tax, and the potential incentive. Note that in this paper, we consider a fixed cost and a variable cost associated with the implementation of sustainable energy solutions. The fixed cost represents the initial investment that has to be made to support the adoption of the technology, while the variable cost is determined by the unit price of the equipment and the number of units to be purchased. Each solution lowers the emission from the associated energy consumption source by a constant rate (L_{jk}) for a given period.

To consider the hierarchical nature of the decision-making process in this problem and the existing competition among the ports, we propose a bilevel programming model. In this model, the regulator acts first as the leader and attempts to make optimal decisions, and then the ports, as the followers, react to the regulator's decisions in a way that is individually optimal. Due to the consideration of policy transparency, which indicates that both the leader and the followers have access to each other's objectives and green technology [81], perfect information is assumed in this paper. Table 6.1 shows the notation used in developing the optimization model.

The port energy demand is modeled as a linear function of the port service price for handling each container (Equation (6.2.1)) [174]. If there is more than one port in the region (i.e., N ports), we can obtain each port demand by Equation (6.2.2) [175]. These equations include

$$q = \frac{a-p}{b}, \text{and} \tag{6.2.1}$$

$$q_i = \begin{cases} 0 & p_i > a \ \ or \ \ p_i > p_j, \ \ i \neq j \\ \dfrac{a-p_i}{Nb} & p_i = p_j, \ \ i \neq j \\ \dfrac{a-p_i}{b} & p_i \leq min(a, p_j), \ \ i \neq j \end{cases} . \tag{6.2.2}$$

The emission level after implementing green solutions at port i equals the initial emission level at the port (i.e., e_i^0) minus the mitigated emission (Equation (6.2.3)). Tax and incentive for each port are assumed to be linearly dependent on the gap between the associated emission cap and emission level as presented in

$$e_i^t = e_i^0 - (\sum_j \sum_k R_{jk} L_{jk} x_{ijk}) q_i, \tag{6.2.3}$$

$$\tau_i = \tilde{\tau}(e_i^t - e_i^c), \text{and} \tag{6.2.4}$$

$$s_i = \tilde{s}(e_i^c - e_i^t). \tag{6.2.5}$$

We denote the profit of port i by π_i, which is calculated by subtracting the emission tax and the

Table 6.1: Nomenclature

i	Ports, $i = 1, \ldots, N$
j	Emission source at the port, $j = 1, \ldots, M$
k	Emission abatement solution, $k = 1, \ldots, U$
l	Index for weights in the regulator objective function, $l = 1, \ldots, L$
d	Iteration number in solution algorithm
UP	Superscript for upper bound of variables
LO	Superscript for lower bound of variables
a	Constant term in the port energy demand function
b	Coefficient term in the port energy demand function
r	Scaling coefficient, $r \in (0, 1]$
M	A very large number
B	Regulator budget dedicated to emission reduction at ports in the region
β_i	Emission cap upper bound for port i
FC_{jk}	Fixed cost of jk^{th} solution implementation
VC_{jk}	Variable cost of jk^{th} solution implementation (per unit)
R_{jk}	Emission reduction rate of jk^{th} solution per TEU
L_{jk}	Service capacity of a unit of jk^{th} solution (#TEUs per unit of solution)
Q	Maximum energy demand for a port
$\tilde{s}$	Incentive rate (per unit of reduced emission)
$\tilde{\tau}$	Tax rate (per unit of excess emission)
s_i	Total incentive received by port i
τ_i	Total tax paid by port i
ϵ	A very small value
$e^{c,UP}$	Initial upper bound for e^c
$e^{c,LO}$	Initial lower bound for e^c
ω_l	Weight associated with term l in the regulator objective function
π_i^*	Maximum profit that port i can potentially receive
p_i^*	Service price for port i that results in π_i^*
q_i^*	Service demand for port i that results in π_i^*
s_i^*	Incentive for port i that results in π_i^*
e_T	Total emission level from ports' activities in the region
e_i^c	Emission cap assigned to port i
e_i^0	Emission level at port i before abatement procedure
e_i^t	Emission level at port i after abatement procedure
y_{ijk}	Implementation status of jk^{th} solution at port i
x_{ijk}	Number of components installed from jk^{th} solution at port i
p_i	Port i service price
λ_i^τ	Paying tax status for port i
λ_i^s	Paying incentive status for port i
z_{LBD}	Objective function value of the lower-bounding problem
z_{UBD}	Objective function value of the upper-bounding problem
σ	Auxiliary variable for handling multi-objective lower-level model
q	Energy demand for a port
π_i	Port i profit

emission abatement costs, if any, from the total port revenue and incentive as shown in

$$\begin{aligned}\pi_i &= p_i q_i + s_i - \tau_i \\ &- \Big[(\sum_j \sum_k FC_{jk} y_{ijk}) + (\sum_j \sum_k VC_{jk} x_{ijk})\Big]. \end{aligned} \tag{6.2.6}$$

Then, the bilevel model for $i = 1, \ldots, N$, $j = 1, \ldots, M$, and $k = 1, \ldots, U$ can be formulated as follows:

$$\min_{e_i^c} \quad \omega_1 \sum_i \frac{e_i^t}{e_i^0} + \omega_2 \sum_i \frac{(e_i^c - e_i^0)^2}{(e_i^0)^2} + \omega_3 (\frac{Q - \sum_i q_i}{Q}) + \omega_4 \sum_i \frac{e_i^c}{e_i^0}, \tag{6.2.7}$$

$$s.t. \quad \sum_i s_i \leq B, \tag{6.2.8}$$

$$0 \leq e_i^c \leq \beta_i, \tag{6.2.9}$$

$$\sum_i q_i \leq Q, \tag{6.2.10}$$

$$\min \ \sigma, \tag{6.2.11}$$

$$s.t. \ \frac{\pi_i^* - \pi_i}{\pi_i^*} \leq \sigma, \tag{6.2.12}$$

$$x_{ijk} \leq M y_{ijk}, \tag{6.2.13}$$

$$-M\lambda_i^s \leq e_i^t - e_i^c \leq M\lambda_i^\tau, \tag{6.2.14}$$

$$\lambda_i^s + \lambda_i^\tau = 1, \tag{6.2.15}$$

$$0 \leq e_{ij}^t, \text{and} \tag{6.2.16}$$

$$x_{ijk} \in Z^+, y_{ijk}, \lambda_i^s, \lambda_t^i \in \{0,1\}, 0 \leq p_i. \tag{6.2.17}$$

Equations (6.2.7)–(6.2.10) define the upper-level model, and Equations (6.2.11)–(6.2.17) define the lower-level model. Given the regulatory role of the policy-makers, the regulator objective function (i.e., the objective function of the upper-level model) is a convex combination of four normalized terms: 1) the emission level from port activities, 2) the gap between the assigned emission cap and the initial emission level of each port, 3) the gap between the satisfied port service demand and the total demand, and 4) the emission cap assigned to each port (Equation (6.2.7)). Note that the second term is included to model a fair regulator which assigns emission caps based on the port's initial emission level.

The total incentive that the ports can receive is subject to the budget constraint of the regulator (Equation (6.2.8)). The assigned emission caps are subject to their respective upper bounds (Equation (6.2.9)), and should always be positive. The satisfied demand for port service should be less than or equal to the total market demand (Equation (6.2.10)).

In the lower-level model, the goal is to maximize the profit of the ports by

$$\max_{x_{ijk}, y_{ijk}, p_i} (\pi_1, \pi_2, \ldots, \pi_N). \tag{6.2.18}$$

To handle the multi-objective lower-level problem, we reformulate Equation (6.2.18) into Equation (6.2.11) and add Equation (6.2.12) to the lower-level model. In Equation (6.2.12), π^* is a parameter referring to the maximum profit that each port could potentially receive. Parameter π^* is calculated by

$$\pi_i^* = p_i^* q_i^* + s_i^*. \tag{6.2.19}$$

Equation (6.2.13) ensures that the fixed cost of implementing solutions will be considered along with the variable cost. Equation (6.2.14) decides whether the port entity pays emission tax or receives incentives according to its emission level and the emission cap assigned to it, respectively. Equation (6.2.15) ensures that each port either pays taxes or receives incentives. The emission level associated with each polluting source in the port facility cannot be negative (Equation (6.2.16)). Finally, Equation (6.2.17) enforces the range of the variables.

While several solution methodologies exist for linear bilevel programming models (e.g., vertex enumeration, Kuhn-Tucker conditions, and penalty approaches) [81, 176], they are not well studied for a mixed-integer nonlinear bilevel model with a non-convex lower-level problem, as formulated in

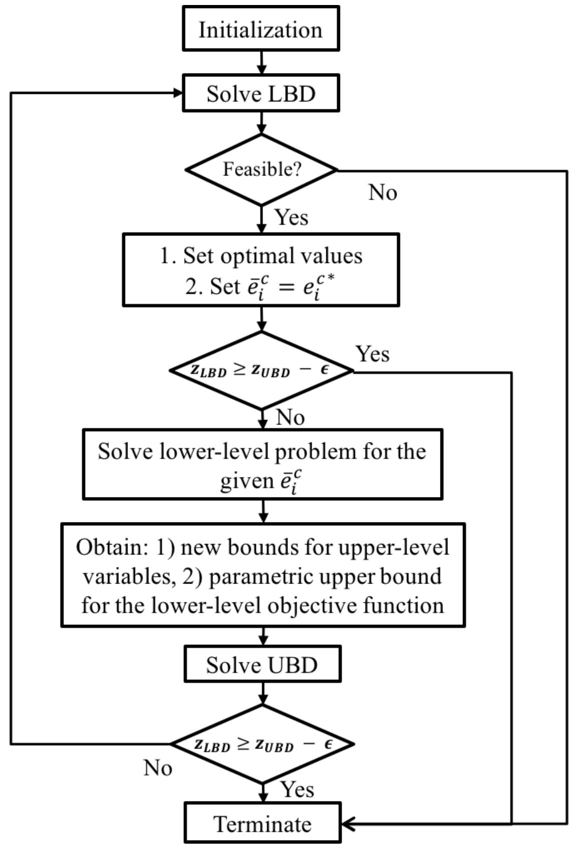


Figure 6.1: Algorithm implemented for solving the bilevel model presented in Equations (6.2.7)–(6.2.17)

the previous discussion. In this paper, we adopt and extend the general algorithm proposed in [177] to formulate a problem-specific solution methodology. As indicated in [177], three assumptions have to be met to ensure the convergence of the algorithm. We illustrate them in the context of this paper as follows:

Assumption 1: Explicit bounds are known for all variables.

Comments: All variables in our problem formulation have box-constrained host sets; hence, the first assumption is met.

Assumption 2: All functions are assumed to be continuous on continuous variables for the given integer variables.

Comments: All of the functions in the developed bilevel model (Equations (6.2.7)–(6.2.17)) are either linear or quadratic on continuous variables; therefore, the second assumption is met.

Assumption 3: Consider $f^l(z^u, z^l)$ as the lower-level objective function as a function of upper-level variables (i.e., z^u) and lower-level variables (i.e., z^l). If some upper-level variables are continuous, there exists some $\bar{\epsilon}^u > 0$ such that for each feasible upper-level variable, i.e., $\bar{z}^u$, at least one of the following two conditions hold:

- For any $\bar{\epsilon}^l > 0$, there exists a feasible vector of lower-level variables, i.e., $\bar{z}^l$, such that

$$f^l(\bar{z}^u, \bar{z}^l) \leq f^{l,*}(\bar{z}^u) + \bar{\epsilon}^l. \tag{6.2.20}$$

- The upper-level objective function value is worse than its optimal value by $\bar{\epsilon}^u$.

Comments: The second condition of the third assumption is met in this paper because of the contradictory objectives of the upper-level and the lower-level, such as the emission level in the first term of the upper-level objective function, i.e., e_i^t.

As shown in Figure 6.1, for the initialization of the algorithm, the upper bound (i.e., z_{UBD}) and the lower bound (i.e., z_{LBD}) for the regulator objective function are set to $+\inf$ and $-\inf$, respectively. At each iteration, the lower-bounding problem (LBD) is solved and if feasible, an optimal solution is obtained, and we set $\bar{e}_i^c = e_i^{c*}$. Then, if the convergence condition is not met, the lower-level model is solved using fixed values for the emission caps (i.e., $\bar{e}_i^c$). Thus, the parametric upper bound for the lower-level objective function, as well as the new bounds of the emission caps, can be obtained. The last step is solving an upper-bounding problem (UBD) and updating the optimal solution. If the convergence is not met, new constraints will be added to the LBD to direct the algorithm toward the optimal solution. The details for each step are discussed further below.

The lower bound is obtained by solving the LBD, a mixed-integer nonlinear program containing the upper-level objective function, constraints of the lower-level model, and constraints of the upper-level model. The convergence of the LBD is achieved by including a parametric upper bound to the optimal objective function of the lower-level program. This parametric upper bound is enforced by adding a logical constraint (Equation (6.2.22)). Note that D is the set of iterations, d is the iteration number, and E_i^d is the host set obtained at iteration d for the upper-level variable e_i^c. The model includes

$$\min_{e^c,x,y,p,\lambda} z_{LBD} \quad = \omega_1 \sum_i \frac{e_i^t}{e_i^0} + \omega_2 \sum_i \frac{(e_i^c - e_i^0)^2}{(e_i^0)^2} + \omega_3 (\frac{Q - \sum_i q_i}{Q}) + \omega_4 \sum_i \frac{e_i^c}{e_i^0}, \tag{6.2.21}$$

$$s.t. \quad (6.2.8) - (6.2.10), (6.2.12) - (6.2.17), \text{and}$$

$$e_i^c \in E_i^d \implies \sigma \leq \sigma^d, \forall d \in D. \tag{6.2.22}$$

In the first iteration of the algorithm, Equation (6.2.22) considers the initial host set for e^c and $\sigma^d = \inf$. However, in the following iterations, this set of equations will force a new upper-bound on the lower-level objective function for the associated ranges of e^c. The parametric upper bound of the lower-level objective function at iteration d is obtained by solving the lower-level model and obtaining the optimal objective function value (i.e., σ^d equals σ^* at iteration d). This lower-level parametric upper bound is based on the optimal solution of the lower-level model for a given e^c and the subsets of the host set of e^c, for which this solution remains lower-level feasible. Assuming $r \in (0, 1]$ as a scaling coefficient for updating the bounds of e_i^c, the new bounds (i.e., E_i^d) for e_i^c can be obtained from Algorithm 1. This algorithm obtains successively tighter bounds for the upper-level variables (i.e., e_i^c) until all of the potential values for e_i^c within the bounds are feasible for the current lower-level optimal decisions.

Algorithm 1 Finding new bounds for e_i^c

```
for i = 1, ..., N do
    Set r = 1.
    repeat
        if \bar{e}_i^c - 0.5r(e_i^{c,UP} - e_i^{c,LO}) < e_i^{c,LO} then
            Set e_i^{c,d,LO} = e_i^{c,LO}.
            Set e_i^{c,d,UP} = e_i^{c,LO} + r(e_i^{c,UP} - e_i^{c,LO}).
        else if \bar{e} + 0.5r(e_i^{c,UP} - e_i^{c,LO}) > e_i^{c,UP} then
            Set e_i^{c,d,LO} = e_i^{c,UP} - r(e_i^{c,UP} - e_i^{c,LO}).
            Set e_i^{c,d,UP} = e_i^{c,UP}.
        else
            Set e_i^{c,d,LO} = \bar{e}_i^c - 0.5r(e_i^{c,UP} - e_i^{c,LO}).
            Set e_i^{c,d,UP} = \bar{e}_i^c + 0.5r(e_i^{c,UP} - e_i^{c,LO}).
        Check if the lower-level optimal decisions for all of the realizations of e_i^c within the bounds
        remain valid.
        if The range is valid then Terminate the loop else Set r = 0.5r.
    until True;
end
```

The optional upper bound to the optimal solution of the bilevel program is obtained by solving an augmented upper-level problem for fixed upper-level variables. To obtain the upper bound of the optimal objective function, we consider an upper-bounding model for a given $\bar{e}_i^c$ as follows:

$$\begin{aligned} \min_{x,y,p,\lambda} z_{UBD} \quad &= \omega_1 \textstyle\sum_i \frac{e_i^t}{e_i^0} + \omega_2 \textstyle\sum_i \frac{(\bar{e}_i^c - e_i^0)^2}{(e_i^0)^2} \\ &\quad + \omega_3 (\frac{Q - \sum_i q_i}{Q}) + \omega_4 \textstyle\sum_i \frac{\bar{e}_i^c}{e_i^0}, \end{aligned} \tag{6.2.23}$$

$$s.t. \quad (6.2.8), (6.2.10), (6.2.12), (6.2.13), (6.2.15), (6.2.16), (6.2.17),$$

$$0 \le \bar{e}_i^c \le \beta_i, \tag{6.2.24}$$

$$\sigma \le \sigma^d + \epsilon_f^l, \text{ and} \tag{6.2.25}$$

$$-M\lambda_i^s \leq e_i^t - \bar{e}_i^c \leq M\lambda_i^\tau. \tag{6.2.26}$$

As shown in Figure 6.1, after solving the UBD, the convergence condition is checked. If it is not met, a new logical constraint (Equation 6.2.22) based on σ^d and the new bounds of e^c will be added to the LBD to begin the next iteration.

Note that bilevel models may not possess a solution even when the functions are continuous, the constraint region of the problem is nonempty and compact, and the follower has some room to respond for all decisions taken by the leader [81]. This happens when the set of all solutions to the follower problem for a fixed leader decision consists of some nontrivial subset of a hyperplane. This means that the follower is indifferent to any point on that hyperplane while the leader might not feel the same indifference with respect to its objective function. However, the leader has no way to induce the follower to change its decisions. The points on this hyperplane are called indifference points which lead to the nonexistence of solutions. A simple way to see whether a solution, $(e_i^{c*}, x_{ijk}^*, y_{ijk}^*, p_i^*, \lambda_,^{\tau*} \lambda_i^{s*})$, to the model presented in Equations (6.2.7)–(6.2.17) is unique is to solve the following problem in which S is the constraint region of the bilevel problem and σ is the lower-level objective function:

$$\begin{aligned}
&\min\{\sigma : (e_i^c, x_{ijk}, y_{ijk}, p_i, \lambda_i^\tau, \lambda_i^s) \in S,\\
&\omega_1 \sum_i \frac{e_i^t}{e_i^0} + \omega_2 \sum_i \frac{(e_i^c - e_i^0)^2}{(e_i^0)^2}\\
&+\omega_3(\frac{Q - \sum_i q_i}{Q}) + \omega_4 \sum_i \frac{e_i^c}{e_i^0}\\
&= \omega_1 \sum_i \frac{e_i^{t*}}{e_i^0} + \omega_2 \sum_i \frac{(e_i^{c*} - e_i^0)^2}{(e_i^0)^2}\\
&+\omega_3(\frac{Q - \sum_i q_i^*}{Q}) + \omega_4 \sum_i \frac{e_i^{c*}}{e_i^0}\}.
\end{aligned} \tag{6.2.27}$$

If the corresponding solution produces an objective function value that is less than the objective function value associated with $(e_i^{c*}, x_{ijk}^*, y_{ijk}^*, p_i^*, \lambda_,^{\tau*} \lambda_i^{s*})$, then the uniqueness condition does not hold.

Table 6.2: Information pertaining to sustainable energy solutions for port entities

	Fixed cost ($thousands)	Variable cost ($thousands)	Emission reduction rate (% of current emission rate)	Service capacity (annual #TEUs per unit of solution)
Onshore power supply	2,000	800	98%	52,344
LNG-fueled trucks	2,000	211	50%	653
LNG-fueled yard tractors	1,800	120	43%	7,022
Hybrid-electric tugboat	0	2,000	44%	72,300
LNG-fueled locomotives	7,296	5,000	92%	81,338

6.3 Case Study

In this section, we will demonstrate and evaluate the performance of the proposed approach in reducing emission and designing efficient tax and incentives through two simulation-based case studies: 1) a region with one port, and 2) a region with two ports. For both cases, we consider the following sustainable energy solutions: onshore power supply (OPS) for cold-ironing vessels, LNG-fueled trucks, LNG-fueled yard tractors, hybrid-electric tugboats, and LNG-fueled locomotives. Onshore power supply provides power to vessels at the berth through shore-to-ship power cables in which auxiliary engines on-board can be turned off, which leads to a significant reduction of emissions from diesel fuels. Currently, many industrial ports around the globe, including Port of Antwerp, Port of Gothenburg, POLA, and Port of Seattle, are testing and moving toward integrating OPS [45, 178] technologies into their terminal electricity distribution systems. Alternative fuels such as LNG provide another sustainable and cost-effective way for mitigating GHG emissions and other polluting substances, such as NO_x and PM from traditional, diesel-fueled trucks and tractors [179]. The hybrid-electric tugboat is a recently presented solution recommended by POLA and Port of Long Beach (POLB). The preliminary evaluation results indicated that hybrid-electric tugboats can significantly decrease NO_x, CO_2, and PM [180]. Finally, LNG-fueled locomotives can also reduce air emissions and are sustainable alternatives to current diesel-fueled locomotives, as suggested by a study conducted by the Port of Tarragona [181]. The specific costs, emission reduction rates, and service capacity associated with these sustainability solutions are provided in Table 6.2 ([179], [181], [45])

The effectiveness of both the economic policies and green solutions is studied for a one-year period. Model (6.2.7)–(6.2.17) and the solution algorithm have been implemented in GAMS [151]. The Branch-And-Reduce Optimization Navigator (BARON) [182] in GAMS is used for solving the MINLP models at each step of the algorithm [183]. The algorithm has been carried out on a Linux server with 384 GB of RAM and 40 Intel Xeon E5-2690 processors (10 cores per socket) at 3.00 GHz. The time for the algorithm to converge to an optimal solution varies between 1.43 seconds for the single-port case study to 8 hours and 12 minutes for the two-port case study. This convergence time significantly depends on the input parameters such as weights in the government objective function as well as tax and incentive rates.

6.3.1 Case 1: Single-Port Region

As an example of a large container port in a region, we consider the Port of Houston, which is the largest U.S. export port. Using the port operating revenue and the energy demand information between 2003 and 2013 ([142], [143]), we performed a linear regression analysis that considers the inflation rates in order to obtain the y-intercept and the coefficient terms in Equation (6.2.1). Specifically, a and b in Equation (6.2.1) are set to \$123.89 and $\$3.06 \times 10^{-6}$, respectively. As an example of a harmful polluting substance that has not been sufficiently mitigated, we focus on the emission of NO_x. However, the proposed model, solution approach, and policies are applicable to other air pollutants, as well. The emission production rates for each polluting source at each respective port is given in Table 6.3. According to this table, ocean-going vessels are accredited as the most polluting sector of the Port of Houston, as they produce a significant amount of NO_x. The initial NO_x level from OGVs, HDVs, CHEs, harbor crafts, and locomotives amount to 8,113 (tons). In the regulator

Table 6.3: NO_x emission rates from different sources at the Port of Houston (2013)

Inventory Component	NO_x (tons/TEUs)
OGV	0.002399
HDV	0.000600
CHE	0.000674
HC	0.000184
Locomotive	0.000299

objective function (Equation (6.2.7)), we set the following weight parameters: $\omega_1 = 0.1$, $\omega_2 = 0.25$, $\omega_3 = 0.25$, and $\omega_4 = 0.4$. The selection of these parameters prioritizes the regulator's role to promote emission reduction through economic incentives. We test the following four combinations of tax and incentive policies:

- Case 1.1) $\tilde{\tau} = 0$ and $\tilde{s} = 0$ (\$thousands/tons of NO_x)
- Case 1.2) $\tilde{\tau} = 0$ and $\tilde{s} = 10$ (\$thousands/tons of NO_x)
- Case 1.3) $\tilde{\tau} = 10$ and $\tilde{s} = 0$ (\$thousands/tons of NO_x)
- Case 1.4) $\tilde{\tau} = 10$ and $\tilde{s} = 10$ (\$thousands/tons of NO_x)

Table 6.4 shows the results for these four test cases. Case 1.1 serves as the performance benchmark where both tax and incentive rates are set to 0. We can observe that despite the assignment of an emission cap (1623 tons), due to the lack of the economic stimulation, the port chooses not to invest in green solutions (AB = \$0) and its emission level remains unchanged from the initial value, i.e., $e^t = e^0 = 8113$ tons. The port's profit comes from the revenue of handling all of the 1,952,122 containers (Equation (6.2.6)). Case 1.2 analyzes the port behavior in the presence of incentive and no tax. We observe that the same results are obtained in this case as Case 1.1. The results suggest that for this particular problem setting when there is no emission tax and the incentive rate is not as competitive, the port will not be motivated to mitigate its emission level to meet the emission cap. Cases 1.3 and 1.4 show that the reduction in emission level can be achieved when the emission tax is enforced, both in the presence and absence of an incentive. In both cases, the port has to invest \$32.4 million to provide OPS for 38 container vessels for emission abatement and pay \$18.14 million in emission tax for an emission level e^t of 3,436 tons. This investment causes a decline in port profit from \$230.2 million to \$179.66 million. The optimal port service price per container is obtained to be \$120, and the total port demand is satisfied in all of the four instances.

Additional results are obtained and depicted in Figures (6.2) and (6.3) to further analyze the influence of different combinations of tax and incentive rates ranging from 0 to 20 thousand dollars per tons of NO_x emission. Figure (6.2) illustrates the variations of port emission with regards to

Table 6.4: Results for the single-port region

Case No.	e^t (tons)	e^c (tons)	p (\$thousands)	q (# of containers)	π (\$thousands)	AB (\$thousands)	τ (\$thousands)	s (\$thousands)
1.1	8113	1622.80	0.12	1,952,122	230,199	0	0	0
1.2	8113	1622.80	0.12	1,952,122	230,199	0	0	0
1.3	3436	1622.80	0.12	1,952,122	179,661	32,400	18,139	0
1.4	3436	1622.80	0.12	1,952,122	179,661	32,400	18,139	0

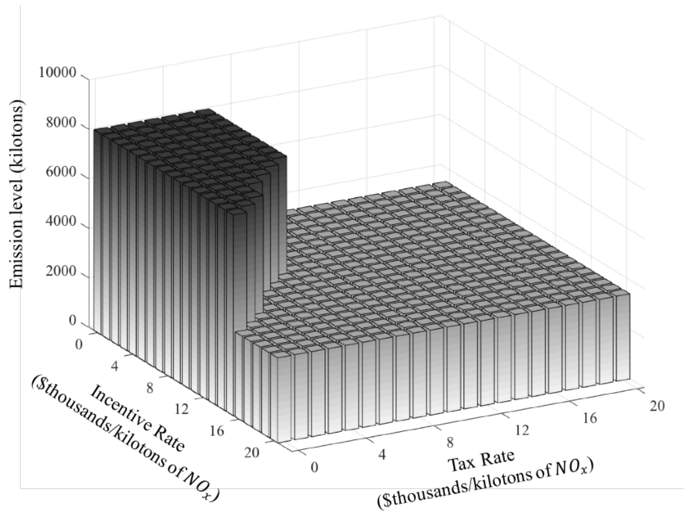


Figure 6.2: Port emission level for different tax and incentive rates

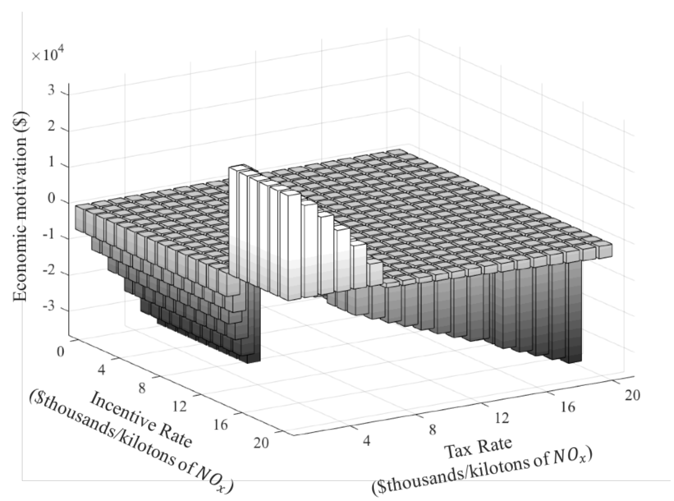


Figure 6.3: Economic motivation for different tax and incentive rates

different tax and incentive rates. We observe that the lowest emission level achieved in this case study is 3,436 tons. It is also noticeable that when the tax rate is low, high incentive rates should be considered to motivate the port (e.g., $\tilde{\tau} = 0$ and $\tilde{s} = \$15000$). Meanwhile, the combination of high tax rates and low incentive rates would also stimulate emission reductions (e.g., $\tilde{\tau} = \$7000$ and $\tilde{s} = \$9000$). Figure (6.3) presents the payment flow between the port and the regulatory authority for different tax and incentive rates. It can be observed that incentives can only be obtained in a few instances when the tax rates are low, and the incentive rates are high. This indicates that in those few instances, tax by itself cannot sufficiently motivate the port to mitigate its emission. Comparing Figures (6.2) and (6.3), we notice that for lower tax and incentive rates, the port is reluctant to initiate emission abatement and is willing to pay the tax instead. However, with the increasing tax or incentive rates, the port becomes more willing to proactively decrease its emission level to avoid emission taxes and to seek the opportunity of meeting the emission cap to receive incentives.

6.3.2 Case 2: Two-Port Region

For the second case study, we consider an instance involving two container ports in the same region: POLA and POLB. These two ports are located side-by-side in San Pedro Bay but are two separate entities and compete with each other for business [184]. According to data for year 2017 ([2],[185],[140]), the number of total containers handled at POLA and POLB, respectively, were 9,343,192 and 7,544,507, while the operating revenue at each respective port amounted to \$475 million and \$381 million. Hence, in the ports' demand function (Equation (6.2.2)), a is set to \$90.84, and b is set to $\$2.87 \times 10^{-6}$. Details of each ports' emission inventories are provided in Table 6.5. Without loss of generality, the weight parameters in the regulator objective function are set for this particular example as follows: $\omega_1 = 0.25$, $\omega_2 = 0.25$, $\omega_3 = 0.25$, and $\omega_4 = 0.25$. Four combinations of tax and incentive rate are considered: Case 2.1: $\tilde{\tau} = 0$ and $\tilde{s} = 0$ (\$thousands/tons

Table 6.5: NO_x emission rates from different sources at POLA and POLB (2017)

Inventory Component	LA: NO_x (tons/TEUs)	LB: NO_x (tons/TEUs)
OGV	0.00033	0.00056
HDV	0.00016	0.00015
CHE	0.00005	0.00005
HC	0.00007	0.00008
Locomotive	0.00009	0.00008

Table 6.6: Results for the two-port region

Case No.	$\mathbf{e_T}$ (tons)	$(e_1^t; e_2^t)$ (tons)	$(e_1^c; e_2^c)$ (tons)	$(p_1; p_2)$ (\$thousands)	$(q_1; q_2)$ (# of containers)	$(\pi_1; \pi_2)$ (\$thousands)	$(AB_1; AB_2)$ (\$thousands)	$(\tau_1; \tau_2)$ (\$thousands)	$(s_1; s_2)$ (\$thousands)
2.1	**11,307**	(4,886;6,421)	(4,886;3,475)	(0.05;0.05)	(7,691,361;7,691,361)	(354,721;354,658)	(0;0)	(0;0)	(0;0)
2.2	**7,170**	(4,515;2,655)	(3,126;6,389)	(0.05;0.05)	(6,979,576;6,979,576)	(354,404;354,404)	(4,400;41,800)	(0;0)	(0;37,337)
2.3	**5,419**	(2,691;2,728)	(3,268;3,484)	(0.05;0.05)	(7,471,608;7,471,608)	(330,687;329,287)	(27,800;29,200)	(0;0)	(0;0)
2.4	**5,298**	(2,706;2,592)	(2,760;3,962)	(0.05;0.05)	(7,513,368;7,513,368)	(335,303;335,220)	(23,520;36,760)	(0;0)	(538;13,694)

of NO_x), Case 2.2: $\tilde{\tau} = 0$ and $\tilde{s} = 10$ (\$thousands/tons of NO_x), Case 2.3: $\tilde{\tau} = 10$ and $\tilde{s} = 0$ (\$thousands/tons of NO_x), and Case 2.4: $\tilde{\tau} = 10$ and $\tilde{s} = 10$ (\$thousands/tons of NO_x).

Table 6.6 shows the results obtained for this case study. Case 2.1 serves as the performance benchmark and reflects the ports' optimal decisions when there is no tax nor incentive. The total emission level in the region, denoted by e_T, is 11,307 tons of NO_x, which is affected only by the number of handled containers in this case. The abatement costs are zero for both ports, and the maximum port profit is achieved by setting $p_i = \$50$. The number of total handled containers in the region is 13,959,152. We observe that in all of the instances, both ports have decided to set similar service prices (i.e., $p_1 = p_2$) and satisfy an equal amount of demand (i.e., $q_1 = q_2 = \frac{a - p_i}{2b}$). This is in accordance with Equation (6.2.2), as its Pareto optimal solution can be achieved when the ports set similar service prices.

In Case 2.2, POLA invests \$4.4 million and equips 3 vessels with OPS while POLB invests \$41.8 million in providing OPS for 35 vessels, purchasing 50 LNG-fueled yard tractors, and investing in 2 hybrid-electric tugboats. By lowering its emission level to 2,655 tons, POLB gains an incentive of \$37.34 million. The overall regional emission is reduced by 32%.

In Case 2.3, the positive tax rate results in a significant reduction of emission levels from both ports. More specifically, POLA mitigates its NO_x level by investing \$27.8 million in 50 LNG-fueled tractors, one hybrid-electric tugboat, and providing OPS for 20 vessels. POLB spends \$29.2 million to provide OPS to 34 vessels. The overall regional emission is further reduced to 5,416 tons, which is about 52% of the initial emission level.

The minimum emission level of 5,298 tons is achieved in Case 2.4. With positive tax and incentive rates, both ports lower their emission levels below the emission cap to receive incentives. POLA provides OPS for 34 vessels and purchases 31 LNG-fueled yard tractors through the investment of \$23.5 million in emission abatement. On the other hand, POLB invests \$36.8 million in obtaining OPS for 34 vessels and purchasing 48 LNG-yard tractors. This allows both ports to collect incentives.

In Case 2.1-Case 2.4, we have analyzed the optimal decisions in the presence of uniform (i.e., equal) tax and incentive rates for the competing ports. However, in practice, governments and regulators might impose unilateral (i.e.,unequal) emission policies for port entities such as emission control areas and region-specific carbon taxes. In the following discussion, we will investigate the overall optimal operational (i.e., economic and environmental) strategies for POLA and POLB under unilateral emission policies as profit-maximizing decision makers. In this way, the effects of uniform and unilateral emission regulations on the profits, cargo volumes and emissions can be compared in a competitive environment. More specifically, Case 2.5-2.7 are presented in the following discussion to study how port entities would respond to unilateral emission policies when one port has a higher incentive rate, a higher tax rate, and higher incentive and tax rates simultaneously. The results for these cases are shown in Figures 6.4 and 6.5.

- Case 2.5) $\tilde{\tau}_1 = 10$, $\tilde{\tau}_2 = 15$, $\tilde{s}_1 = 10$ and $\tilde{s}_2 = 15$ (\$thousands/tons of NO_x)
- Case 2.6) $\tilde{\tau}_1 = 10$, $\tilde{\tau}_2 = 10$, $\tilde{s}_1 = 10$ and $\tilde{s}_2 = 15$ (\$thousands/tons of NO_x)
- Case 2.7) $\tilde{\tau}_1 = 10$, $\tilde{\tau}_2 = 15$, $\tilde{s}_1 = 10$ and $\tilde{s}_2 = 10$ (\$thousands/tons of NO_x)

It can be observed that in all three cases, the regulatory policies have facilitated the adoption of sustainable energy solutions for both POLA and POLB to reduce their emission levels below their associated emission caps to avoid the emission tax, i.e., τ_1 and τ_2 are both 0. Furthermore, in case 2.5, due to the elevated tax and incentive rates for POLB, the overall emission of the region e_T can be reduced to 5276 tons, which is the lowest emission level compared with the other policies for the two-port region. As POLB invests more in emission reduction, it receives more incentive, which results in a increased profit of $336,152,000 in this case. Moreover, ports set similar service prices and demand (i.e., $p = \$50$, $q = 7,471,609$ TEUs) which is in accordance with our previous discussion.

It can be also observed that under the proposed model, increasing the tax or incentive rate for one port does not significantly impact the overall performance of the other port. This observation is

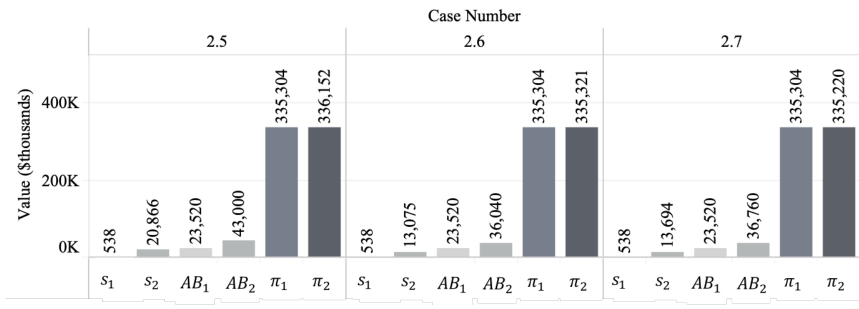


Figure 6.4: Economic performance of POLA and POLB under unilateral tax and incentive rates

Figure 6.5: Environmental performance of POLA and POLB under unilateral tax and incentive rates

consistent with the port's revenue model represented in Equation (6.2.2). After the optimal service price and energy demand are determined, each port authority attempts to seek its maximum profit (Equation (6.2.19)) by acting in its own best interest. In this process, a port entity does not have to take into account the rate of tax or incentive allocated to the other port entities or their responses in mitigating emissions. This observation verifies the model presented in Equations (6.2.7)-(6.2.17). It also provides the regulatory authority with the flexibility and the option to assign uniform and unilateral tax and incentive rates to different ports, knowing that the required emission level, tax rate, and incentive rate for one port does not significantly impact the other ports in the region.

The results from the single-port region and the two-port region cases indicate that emission tax is capable of reducing emission level on its own; however, the combination of tax and incentive would promote further emission reduction without impairment for the ports. In all of the instances, the most effective choice among green solutions is the onshore power supply. This is due to the fact that the emission mitigation capacity of OPS outweighs its overall investment cost, making it the most appealing green technology choice for port entities to adopt. Contrarily, LNG-fueled locomotives were not chosen in any of these cases despite its high service capacity and high reduction rate.

This is in accordance with the fact that vessels are commonly more substantial contributors to NO_x emissions compared to other polluting sources at ports.

6.4 Conclusion

This paper develops a novel hybrid economic approach to assist both the regulatory authority and the stakeholders of port entities to strike a balance between energy sustainability and fair competition in the competitive environment of a region consisting of multiple ports. Simulation results obtained in Section IV indicate that the proposed approach is capable of effectively promoting green energy and reducing emissions while ensuring port customers' welfare and sustainable growth. By looking into different combinations of tax and incentive policies in both case studies, we can conclude that emission tax is a more effective approach for emission mitigation than incentive. Higher rates of incentive are required to push the adoption of sustainable energy solutions when there is no tax, while even low tax rates can provide sufficient stimulation for the ports. Furthermore, the combination of tax and incentive can perform better and further motivate emission reduction. In terms of the selection of green solutions, our results indicate that the port tends to invest in solutions that strike the right balance between emission mitigation and overall cost. For instance, ports in our case studies have invested more in implementing onshore power supply due to its significant effectiveness in mitigating emissions with a relatively low investment cost.

We envision that our research effort presented in this paper will facilitate the transformation of traditional industrialized ports into an integral contributing component of a sustainable ecosystem. The proposed research creates the necessary structural and functional framework not only to strengthen the particular application of maritime ports, as demonstrated in this paper, but also to provide critical insights into revitalizing other large energy-intensive facilities that exhibit significant impacts on the prosperity and well-being of local communities and are also subject to the ever-changing regulatory environment.

For future work, one can further explore variations of the assumptions adopted in this manuscript, such as the linear relationship between the port service price and the service demand, and the linearity of the tax and incentive functions. The uncertainties of energy demands, service prices, and sustainable energy solution costs can also be incorporated in the proposed model to determine the optimal installation of sustainable energy solutions under a long-term, dynamic setting.

Chapter 7

Summary and Future Work

This dissertation is directed towards aiding the port authorities, port operators, and regulatory authorities to overcome the challenges that threaten the sustainability and survival of ports in the future era of the competitive and demanding global economy. Chapter 3 of this dissertation can be considered the first attempt to provide a comprehensive definition of a smart port and an empirical assessment of current trends at the international level. To this end, four main activity domains (i.e., operations, energy, environment, and safety and security) and the related sub-domains of a smart port were identified based on smart port best practices; afterward, the Smart Port Index was developed as the convex combination of the sub-indices. Index calculation is achieved mainly through the measurement of the KPIs collected from the literature. The numerical example included the study of 14 ports selected among the top 100 busiest ports in the world in terms of the total number of annual TEUs. Port selection criteria were the availability of data given on the ports' websites and diversity in the location of the ports. After index measurements, an analysis was conducted in order to understand the relationship between the geographical, governmental, economic, and energy-related variables, and the dependent SPI variable. It was noticed that regional variables and government policies can affect the port performance and that in general, ports located in countries that are wealthier, open to innovation, environmentally-friendly, and energy efficient have higher SPI values. For future research, one can investigate other possible activity domains to be included in the smart port concept such as sustainability, human resources (e.g., knowledgeable employees, creativity, training opportunities), and institutional aspects (e.g., corporate governance, harmony with the community, supply chain partnerships). Moreover, if one has access to more comprehensive data for computing more KPIs, the empirical research can be extended to enhance the analysis presented in Chapter 3. Furthermore, there is a need to further explore both the barriers of implementation and impacts of a smart port on the related matters; for instance, we can target topics such as the impact of smart ports on traditional institutional and human factors and the influence of smart ports on cities and the surrounding municipalities.

In Chapter 4, we have attempted to evaluate the benefits of microgrid integration and how these advantages can be translated into opportunities for the port industry in particular. Our research findings provided an initial assessment on how to transform a traditional industrialized port into a contributing component of a sustainable eco-system through the use of microgrids. In particular, we have implemented a set of metrics from different key operation domains to facilitate the formation of a holistic approach for planning port microgrids. Case studies and simulation results highlighted, in a quantitative way, that through the proposed planning approach, the microgrid can contribute to various aspects of port operation and management such as avoiding facility downtime, improved power quality, cost savings, energy dependency, and emission reduction.

Chapter 5 developed a holistic optimization framework for providing clean and green energy supply to the ports and ocean-going vessels. We attempted to fill the gap in the literature for integrating microgrid and OPS for the ports by optimizing the investment and planning of microgrid along with OPS and evaluating their benefits for the ports and vessels. This work considered the inherent uncertainties associated with microgrid planning and renewable energy generation, and proposes an efficient solution approach for obtaining optimal decisions and insights for the business stakeholders. Case study and simulation results highlighted that by the proposed methodology, the port microgrid combined with the OPS can mitigate emission levels at ports significantly and enhance the sustainability of the ports.

In Chapter 6, we developed a novel hybrid economic approach to assist both the regulatory authority and the stakeholders of port entities to strike a balance between energy sustainability and fair competition in the competitive environment of a region consisting of multiple ports. Simulation results indicated that the proposed approach is capable of effectively promoting green energy and reducing emissions while ensuring port customers' welfare and sustainable growth. By looking into different combinations of tax and incentive policies in both case studies, we can conclude that emission tax is a more effective approach for emission mitigation than incentive. Higher rates of incentive are required to push the adoption of sustainable energy solutions when there is no tax, while even low tax rates can provide sufficient stimulation for the ports. Furthermore, the combination of tax and incentive can perform better and further motivate emission reduction. In terms of the selection of green solutions, our results indicate that the port tends to invest in solutions that strike the right balance between emission mitigation and overall cost. For instance, ports in our case studies have invested more in implementing onshore power supply due to its significant effectiveness in mitigating emissions with a relatively low investment cost. We envision that our research effort presented in this contribution will facilitate the transformation of traditional industrialized ports into an integral contributing component of a sustainable eco-system. The proposed research creates the necessary structural and functional framework not only to strengthen the particular application of maritime ports, but also to provide critical insights into revitalizing other large energy-intensive facilities that exhibit significant impacts on the prosperity and well-being of local communities and are also subject to the ever-changing regulatory environment. For future work, one can further explore variations of the assumptions adopted in Chapter 6, such as the linear relationship between the port service price and the service demand, and the linearity of the tax and incentive functions. The uncertainties of energy demands, service prices, and sustainable energy solution costs can also be incorporated in the proposed model to determine the optimal installation of sustainable energy solutions under a long-term, dynamic setting.

References

[1] James J Corbett, James J Winebrake, Erin H Green, Prasad Kasibhatla, Veronika Eyring, and Axel Lauer. Mortality from ship emissions: a global assessment. *Environmental science & technology*, 41(24):8512–8518, 2007.

[2] Port of Los Angeles. Inventory of air emission. *Industrial Marketing Management*, 2015. <https://www.portoflosangeles.org/pdf/2015_Air_Emissions_Inventory.pdf> Accessed May 1, 2017.

[3] UNCTAD. Port Marketing and the Challenge of the Third Generation Port. 1992.

[4] UNCTAD. The fourth generation port. *UNCTAD Ports Newsletter*, 19:9–12, 1999.

[5] Cristiane Ferreira da Silva Barros and Cleyton Miranda Barros. Suitability of Brazilian Ports to International Standards of Port Needs: A Case Study in the Port of Salvador. *Journal of Transport Literature*, 7(4):23–49, 2013.

[6] The Motorways of the Sea Digital Multi-Channel Platform. Smart Port, 2015. Retrieved from <http://www.onthemosway.eu/wp-content/uploads/2015/07/1-Smart-Ports-v-2.0.pdf?00cab0> (Accessed April 8, 2019).

[7] Nikos Hatziargyriou, Hiroshi Asano, Reza Iravani, and Chris Marnay. Microgrids. *IEEE power and energy magazine*, 5(4):78–94, 2007.

[8] Smith, T. W. P., Jalkanen, J. P., Anderson, B. A., Corbett, J. J., Faber, J., Hanayama, S., ... & Raucci, C. Third IMO GHG study 2014. *International Maritime Organization (IMO)*,

2014. London, http://www. iadc. org/wp-content/uploads/2014/02/MEPC-67-6-INF3-2014-Final-Report-complete. pdf.

[9] Jasmine Siu Lee Lam and Theo Notteboom. The greening of ports: A comparison of port management tools used by leading ports in asia and europe. *Transport Reviews*, 34(2):169–189, 2014.

[10] United States Environmental Protection Agency. Economic incentives. *Transportation Research Part D: Transport and Environment*, 2017. Web. <`https://www.epa.gov/environmental-economics/economic-incentives`> Accessed May 1, 2017.

[11] W Scott Spangler, Jeffrey T Kreulen, Ying Chen, Larry Proctor, Alfredo Alba, Ana Lelescu, and Amit Behal. A Smarter Process for Sensing the Information Space. *IBM Journal of Research and Development*, 54(4):1–13, 2010.

[12] Taewoo Nam and Theresa A Pardo. Conceptualizing Smart City with Dimensions of Technology, People, and Institutions. *Proceedings of the 12th Annual International Digital Government Research Conference: Digital Government Innovation in Challenging Times*, 2011. (pp. 282-291). ACM.

[13] Robert E Hall, B Bowerman, J Braverman, J Taylor, H Todosow, and U Von Wimmersperg. The Vision of a Smart City (No. BNL-67902; 04042). 2000. Brookhaven National Lab., Upton, NY.

[14] Center on Governance. SmartCapital Evaluation Guidelines Report: Performance Measurement and Assessment of SmartCapital, Ottawa Smart Community Demonstration Project, 2003. University of Ottawa, Ottawa, Canada. Retrieved from <`http://www.christopherwilson.ca/papers/Guidelines_report_Feb2003.pdf`> (Accessed April 8, 2019).

[15] Rosabeth Moss Kanter and Stanley S Litow. Informed and Interconnected: A Manifesto for Smarter Cities. *Harvard Business School General Management Unit Working Paper*, 2009. (09-141).

[16] MedMaritime SMART PORT. Action Plan towards the SMART PORT Concept in the Mediterranean Area, 2016. Retrieved from <http://www.medmaritimeprojects.eu/download/ProjectSmartport/RESERVED_Folder/D1_1_Smart_port_criteria_Final.pdf> (Accessed April 8, 2019).

[17] Hamburg Port authority. smartPort Logistics, 2016. Retrieved from <https://www.hamburg-port-authority.de/en/hpa-360/smartport/> (Accessed April 8, 2019).

[18] Port of Rotterdam. Smart Port, 2016. Retrieved from <http://smart-port.nl/en/> (Accessed April 8, 2019).

[19] Hamburg Port authority. smartPort Energy, 2016. Retrieved from <https://www.hamburg-port-authority.de/en/hpa-360/smartport/> (Accessed April 8, 2019).

[20] World Port Hackathon. World Port Hackathon, 2016. Retrieved from <http://worldporthackathon.com> (Accessed April 8, 2019).

[21] Port of Amsterdam. Port of Amsterdam Accelerates Energy Transition, 2017. Retrieved from <https://www.portofamsterdam.com/en/press-release/port-amsterdam-accelerates-energy-transition> (Accessed April 8, 2019).

[22] Amsterdam Smart City. Smart Port: Port of Amsterdam, 2016. Retrieved from <https://amsterdamsmartcity.com/projects/smart-port-port-of-amsterdam> (Accessed April 8, 2019).

[23] AGT International SmartPort Solution. Optimizing Port Ecosystems with IoT Analytics, 2013. Retrieved from <https://www.agtinternational.com/wp-content/uploads/2014/10/AGT_AAG_SmartPrt-2_19oct_15.pdf> (Accessed April 8, 2019).

[24] Pablo Fernández, José Miguel Santana, Sebastián Ortega, Agustín Trujillo, José Pablo Suárez, Conrado Domínguez, Jaisiel Santana, and Alejandro Sánchez. Smartport: A Platform for Sensor Data Monitoring in a Seaport Based on FIWARE. *Sensors*, 16(3):417, 2016.

[25] Kalmar Global. Kalmar SmartPort Automation, 2018. Retrieved from <https://www.kalmarglobal.com/automation/kalmar-smartport/> (Accessed April 8, 2019).

[26] Arelsa Co. Marinas/Smart Port, 2016. Retrieved from http://www.arelsa.com/visin-empresarial-eng> (Accessed April 8, 2019).

[27] L. Lama. Shore-to-ship Power and Smart Port Solutions, 2016. Retrieved from <https://new.abb.com/substations/port-electrification-and-shore-to-ship-power> (Accessed April 8, 2019).

[28] M. Montesinos. SmartPort: Port Information in Your Hand, 2016. Retrieved from <https://www.porttechnology.org/technical_papers/smartport_port_information_in_your_hand#download_article> (Accessed April 8, 2019).

[29] The Maritime Executive. Singapore MPA Unveils Smart Port Initiatives, 2015. Retrieved from <http://www.maritime-executive.com/article/singapore-mpa-unveils-smart-port-initiatives> (Accessed April 8, 2019).

[30] L. Ngcobo. TNPA's Western Cape Ports Now 'smartPORTS', 2015. Retrieved from <http://www.transnetnationalportsauthority.net/CorporateAffairs/Press%20Releases/Archives/Western%20Cape%20ports%20now%20IPMS%20SmartPorts.pdf> (Accessed April 8, 2019).

[31] J. Magyar. Becoming a Smart Port, 2015. Retrieved from <https://www.digitalistmag.com/industries/travel-and-transportation/2015/08/05/becoming-smart-port-03249293> (Accessed April 8, 2019).

[32] Smart Port Hackathon. Smart Port Hackathon, 2017. Retrieved from <https://www.mpa.gov.sg/web/portal/home/media-centre/news-releases/detail/a25a7b1a-ada1-4787-a734-350ba224450d> (Accessed April 8, 2019).

[33] Homeland Security Committee. Homeland Security Committee Passes Smart Port Security Act, 2012. Retrieved from <https://www.hstoday.us/channels/us-coast-guard/house-passes-smart-port-security-act/> (Accessed April 8, 2019).

[34] A. Burger. Port of Los Angeles Microgrid Project Nears Finish Line, 2018. Retrieved from <https://microgridknowledge.com/microgrid-port-of-los-angeles/> (Accessed April 18, 2019).

[35] Muni-Fed Antea Group Energy Partners and The Port of Long Beach. Microgrid Technology White Paper, 2016. Retrieved from <http://www.polb.com/civica/filebank/blobdload.asp?BlobID=13595> (Accessed April 18, 2019).

[36] B. M. Page. Port of San Diego to Install a Solar-Powered Microgrid with $5 Million Grant from California Energy Commission, 2018. Retrieved from <https://www.portofsandiego.org/press-releases/general-press-releases/port-san-diego-install-solar-powered-microgrid-5-million> (Accessed April 18, 2019).

[37] K. Tweed. Can Rotterdam's Port Become a Virtual Power Plant?, 2013. Retrieved from <https://spectrum.ieee.org/energywise/energy/the-smarter-grid/rotterdam-port-looks-to-become-a-virtual-power-plant> (Accessed April 18, 2019).

[38] Roberto Bernacchi. Shore-to-ship power & Smart Ports, April 2017. Retrieved from <https://library.e.abb.com/public/ef42205027df40fcaea5548681ea74ba/S2SP_SP_External_new_brand_19042017.pdf> (Accessed April 18, 2019).

[39] G. Parise, L. Parise, L. Martirano, P. B. Chavdarian, C. Su, and A. Ferrante. Wise Port and Business Energy Management: Port Facilities, Electrical Power Distribution. *IEEE Transactions on Industry Applications*, 52(1):18–24, Jan 2016.

[40] Nor Baizura Binti Ahamad, Josep M Guerrero, Chun-Lien Su, Juan C Vasquez, and Xiao Zhaoxia. Microgrids technologies in future seaports. In *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)*, pages 1–6. IEEE, 2018.

[41] Mohammad-Hassan Khooban, Tomislav Dragicevic, Frede Blaabjerg, and Marko Delimar. Shipboard microgrids: A novel approach to load frequency control. *IEEE Transactions on Sustainable Energy*, 9(2):843–852, 2017.

[42] Zheming Jin, Giorgio Sulligoi, Rob Cuzner, Lexuan Meng, Juan C Vasquez, and Josep M Guerrero. Next-generation shipboard dc power system: Introduction smart grid and dc microgrid technologies into maritime electrical networks. *IEEE Electrification Magazine*, 4(2):45–57, 2016.

[43] Nor Baizura Ahamad, Muzaidi Othman, Juan C Vasquez, Josep M Guerrero, and Chun-Lien Su. Optimal sizing and performance evaluation of a renewable energy based microgrid in future seaports. In *2018 IEEE International Conference on Industrial Technology (ICIT)*, pages 1043–1048. IEEE, 2018.

[44] A. Misra, G. Venkataramani, S. Gowrishankar, E. Ayyasam, and V. Ramalingam. Renewable Energy Based Smart Microgrids-A Pathway To Green Port Development. *Strategic Planning for Energy and the Environment*, 37(2):17–32, 2017.

[45] World Ports Climate Initiative. What is OPS?, 2019. <`http://wpci.iaphworldports.org/onshore-power-supply/what-is-ops/`>.

[46] Theo E. Notteboom and Bert Vernimmen. The effect of high fuel costs on liner service configuration in container shipping. *Journal of Transport Geography*, 17(5):325 – 337, 2009.

[47] Chun-Hsiung Liao, Po-Hsing Tseng, and Chin-Shan Lu. Comparing carbon dioxide emissions of trucking and intermodal container transport in taiwan. *Transportation Research Part D: Transport and Environment*, 14(7):493 – 496, 2009.

[48] Carolien Beckx, Luc Int Panis, Jean Vankerkom, Davy Janssens, Geert Wets, and Theo Arentze. An integrated activity-based modelling framework to assess vehicle emissions: Approach and application. *Environment and Planning B: Planning and Design*, 36(6):1086–1102, 2009.

[49] Po-Hsing Tseng and Nick Pilcher. Exploring the viability of an emission tax policy for ships at berth in taiwanese ports. *Int. J. Shipp*, 8:705–722, 2016.

[50] Davide La Torre, Danilo Liuzzi, and Simone Marsiglio. Pollution control under uncertainty and sustainability concern. *Environmental and Resource Economics*, 67(4):885–903, Aug 2017.

[51] Richard T. Carson and Jacob LaRiviere. Structural uncertainty and pollution control: Optimal stringency with unknown pollution sources. *Environmental and Resource Economics*, 71(2):337–355, Oct 2018.

[52] W.T. Chen, Y.P. Li, G.H. Huang, X. Chen, and Y.F. Li. A two-stage inexact-stochastic programming model for planning carbon dioxide emission trading under uncertainty. *Applied Energy*, 87(3):1033 – 1047, 2010.

[53] Winai Homsombat, Tsz Leung Yip, Hangjun Yang, and Xiaowen Fu. Regional cooperation and management of port pollution. *Maritime Policy & Management*, 40(5):451–466, 2013.

[54] Dian Sheng, Zhi-Chun Li, Xiaowen Fu, and David Gillen. Modeling the effects of unilateral and uniform emission regulations under shipping company and port competition. *Transportation Research Part E: Logistics and Transportation Review*, 101:99 – 114, 2017.

[55] Mikiko Kainuma, Yuzuru Matsuoka, Tsuneyuki Morita, and Go Hibino. Development of an end-use model for analyzing policy options to reduce greenhouse gas emissions. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 29(3):317–324, 1999.

[56] Ying Zhou, Lizhi Wang, and James D. McCalley. Designing effective and efficient incentive policies for renewable energy in generation expansion planning. *Applied Energy*, 88(6):2201 – 2209, 2011.

[57] Hossa Almutairi and Samir Elhedhli. Carbon tax based on the emission factor: a bilevel programming approach. *Journal of Global Optimization*, 58(4):795–815, Apr 2014.

[58] David F. Drake, Paul R. Kleindorfer, and Luk N. Van Wassenhove. Technology choice and capacity portfolios under emissions regulation. *Production and Operations Management*, 25(6):1006–1025, 2016.

[59] Carolyn Fischer and Richard G. Newell. Environmental and technology policies for climate change and renewable energy. page 42, 2005.

[60] Natalia Alguacil, Alexis L Motto, and Antonio J Conejo. Transmission expansion planning: A mixed-integer lp approach. *IEEE Transactions on Power Systems*, 18(3):1070–1077, 2003.

[61] Laura Bahiense, Gerson C Oliveira, Mario Pereira, and Sergio Granville. A mixed integer disjunctive model for transmission network expansion. *IEEE Transactions on Power Systems*, 16(3):560–565, 2001.

[62] Grigorios A Bakirtzis, Pandelis N Biskas, and Vasilis Chatziathanasiou. Generation expansion planning by milp considering mid-term scheduling decisions. *Electric Power Systems Research*, 86:98–112, 2012.

[63] Hatice Tekiner, David W Coit, and Frank A Felder. Multi-period multi-objective electricity generation expansion planning problem with monte-carlo simulation. *Electric Power Systems Research*, 80(12):1394–1405, 2010.

[64] C Henggeler Antunes, A Gomes Martins, and Isabel Sofia Brito. A multiple objective mixed integer linear programming model for power generation expansion planning. *Energy*, 29(4):613–627, 2004.

[65] Maryam Torabbeigi, Gino J Lim, and Seon Jin Kim. Drone delivery scheduling optimization considering payload-induced battery consumption rates. *Journal of Intelligent & Robotic Systems*, 97(3):471–487, 2020.

[66] Ellis L Johnson, George L Nemhauser, and Martin WP Savelsbergh. Progress in linear programming-based algorithms for integer programming: An exposition. *Informs journal on computing*, 12(1):2–23, 2000.

[67] IBM. CPLEX Optimizer, 2008. Retrieved from <https://www.ibm.com/analytics/cplex-optimizer> (Accessed April 13, 2019).

[68] The Gurobi Optimizer. Gurobi Optimization, 2018. Retrieved from <https://www.gurobi.com.

[69] George B Dantzig. Linear programming under uncertainty. In *Stochastic programming*, pages 1–11. Springer, 2010.

[70] Evelyn ML Beale. On minimizing a convex function subject to linear inequalities. *Journal of the Royal Statistical Society: Series B (Methodological)*, 17(2):173–184, 1955.

[71] Jacques F Benders. Partitioning procedures for solving mixed-variables programming problems. *Numerische mathematik*, 4(1):238–252, 1962.

[72] M Shahidehopour and Yong Fu. Benders decomposition: applying benders decomposition to power systems. *IEEE Power and Energy Magazine*, 3(2):20–21, 2005.

[73] Sang M Lee. *Goal programming for decision analysis*. Auerbach Publishers Philadelphia, 1972.

[74] Dylan Jones and Mehrdad Tamiz. *Practical goal programming*, volume 141. Springer, 2010.

[75] Michael D McKay, Richard J Beckman, and William J Conover. Comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics*, 21(2):239–245, 1979.

[76] Gino J Lim, Laleh Kardar, Saba Ebrahimi, and Wenhua Cao. A risk-based modeling approach for radiation therapy treatment planning under tumor shrinkage uncertainty. *European Journal of Operational Research*, 280(1):266–278, 2020.

[77] Rebi Daldal, Özgür Özlük, Barış Selçuk, Zahed Shahmoradi, and Tonguç Ünlüyurt. Sequential testing in batches. *Annals of Operations Research*, 253(1):97–116, 2017.

[78] Rebi Daldal, Zahed Shahmoradi, and Tonguç Ünlüyurt. Estimating the expected cost of function evaluation strategies. In *Industrial Engineering in the Big Data Era*, pages 229–239. Springer, 2019.

[79] Jitka Dupačová, Nicole Gröwe-Kuska, and Werner Römisch. Scenario reduction in stochastic programming. *Mathematical programming*, 95(3):493–511, 2003.

[80] GAMS Development Corporation. Scenred, 2002. Retrieved from <`https://www.gams.com/latest/docs/T_SCENRED.html`> (Accessed April 13, 2019).

[81] Jonathan F Bard. *Practical bilevel optimization: algorithms and applications*, volume 30. Springer Science & Business Media, 2013.

[82] Wilfred Candler and Roger Norton. *Multi-level programming and development policy*. The World Bank, 1977.

[83] Kiyotaka Shimizu, Yo Ishizuka, and Jonathan F Bard. *Nondifferentiable and two-level mathematical programming*. Springer Science & Business Media, 2012.

[84] Marwaan Simaan and Jose B Cruz. On the stackelberg strategy in nonzero-sum games. *Journal of Optimization Theory and Applications*, 11(5):533–555, 1973.

[85] José Fortuny-Amat and Bruce McCarl. A representation and economic interpretation of a two-level programming problem. *Journal of the operational Research Society*, 32(9):783–792, 1981.

[86] Eitaro Aiyoshi and Kiyotaka Shimizu. Hierarchical decentralized systems and its new solution by a barrier method. *IEEE Transactions on Systems, Man and Cybernetics*, (6):444–449, 1981.

[87] Jonathan F Bard. Coordination of a multidivisional organization through two levels of management. *Omega*, 11(5):457–468, 1983.

[88] Hanif D Sherali. A multiple leader stackelberg model and analysis. *Operations Research*, 32(2):390–404, 1984.

[89] M. Amini and F. Yousefian. An iterative regularized incremental projected subgradient method for a class of bilevel optimization problems. In *2019 American Control Conference (ACC)*, pages 4069–4074, 2019.

[90] J. A. Braveboy. Worldwide Seaport Congestion. Master's Capstone Thesis. 2015.

[91] Jasmine Siu Lee Lam and Theo Notteboom. The Greening of Ports: A Comparison of Port Management Tools Used by Leading Ports in Asia and Europe. *Transport Reviews*, 34(2):169–189, 2014.

[92] Gracia Buiza, Sara Cepolina, Aleksandar Dobrijevic, M del Mar Cerbán, Olivera Djordjevic, and Cristina González. Current Situation of the Mediterranean Container Ports Regarding the Operational, Energy and Environment Areas. *International Conference on Industrial Engineering and Systems Management (IESM)*, 2015. (pp. 530-536). IEEE.

[93] S Abbasi, M Barati, and Gino J Lim. A Parallel Sectionalized Restoration Scheme for Resilient Smart Grid Systems. *IEEE Transactions on Smart Grid*, 10(2):1660–1670, 2019.

[94] Ji-Yeong Pak, Gi-Tae Yeo, Se-Woong Oh, and Zaili Yang. Port Safety Evaluation from a Captain's Perspective: The Korean Experience. *Safety Science*, 72:172–181, 2015.

[95] J Cho, Gino J Lim, T Biobaku, and S Kim. LNG Inventory Routing Problem under Uncertain Weather Condition. *International Journal of Production Economics*, 204:18–29, 2018.

[96] International Maritime Organization. Maritime Security and Piracy, 2016. Retrieved from <`http://www.imo.org/en/OurWork/Security/Pages/MaritimeSecurity.aspx`> (Accessed April 8, 2019).

[97] T Biobaku, Gino J Lim, S Bora, J Cho, and H Parsaei. An Optimal Sonar Placement Approach for Detecting Underwater Threats under Budget Limitations. *Journal of Transportation Security*, 9(1):17–34, 2016.

[98] Gino J Lim, J Cho, S Bora, T Biobaku, and H Parsaei. Models and Computational Algorithms

for Maritime Risk Analysis: A Review. *Annals of Operations Research*, 271(2):765–786, 2018.

[99] PortTechnology. What is a Smart Port?, 2016. Retrieved from <https://www.porttechnology.org/news/what_is_a_smart_port> (Accessed April 8, 2019).

[100] Jun-Seok Oh, Valerian Kwigizile, and Ahmad Feizi. Sustainable and smart-growth city ranking: Multifaceted transportation performance measures in smart cities, 09 2019.

[101] Statistia. Forecast for Global TEU Capacity of Container Ships from 2016 to 2020, 2017. <https://www.statista.com/statistics/198254/forecast-for-global-number-of-containership-teus-from-2011/> (Accessed April 8, 2019).

[102] The United States Environmental Protection Agency. Learn About Environmental Management Systems, 2016. Retrieved from <https://www.epa.gov/ems/learn-about-environmental-management-systems#what-is-an-EMS> (Accessed April 8, 2019).

[103] European Commission. What is EMAS?, 2017. Retrieved from <http://ec.europa.eu/environment/emas/index_en.htm> (Accessed April 8, 2019).

[104] EcoPorts. Port Environmental Review System (PERS): The Only Port Sector Specific Environmental Management Standard, 2018. Retrieved from <https://www.ecoports.com/pers> (Accessed April 8, 2019).

[105] Jun-Seok Oh, Valerian Kwigizile, Ron Van Houten, Ahmad Feizi, Majid Mastali, et al. Effects of safe bicycle passing laws on drivers' behavior and bicyclists' safety. Technical report, Western Michigan University, 2018.

[106] James J Corbett, James J Winebrake, Erin H Green, Prasad Kasibhatla, Veronika Eyring, and Axel Lauer. Mortality from Ship Emissions: A Global Assessment. *Environmental Science & Technology*, 41(24):8512–8518, 2007.

[107] Ahmad Feizi, Jun-Seok Oh, Valerian Kwigizile, and Shinhye Joo. Cycling environment analysis by bicyclists' skill levels using instrumented probe bicycle (ipb). *International Journal of Sustainable Transportation*, pages 1–11, 2019.

[108] Corrado Schenone, Ilaria Pittaluga, Simona Repetto, and Davide Borelli. Noise Pollution Management in Ports: a Brief Review and The EU MESP Project Experience. *Proceedings of the 21st International Congress on Sound and Vibration, Beijing, China*, 2014. (pp. 13-17).

[109] Per H Olson. Handling of Waste in Ports. *Marine Pollution Bulletin*, 29(6-12):284–295, 1994.

[110] International Maritime Organization. Energy Management Plans and Systems, 2016. Retrieved from <http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Air%20pollution/M6%20energy%20management%20plan%20and%20system%20final.pdf> (Accessed April 8, 2019).

[111] Bruno Fabiano, Fabio Curro, Andrea P Reverberi, and Renato Pastorino. Port Safety and the Container Revolution: A Statistical Study on Human Factor and Occupational Accidents over the Long Period. *Safety Science*, 48(8):980–990, 2010.

[112] Tayfur Altiok. Port security/safety, risk analysis, and modeling. *Annals of Operations Research*, 187(1):1–3, 2011.

[113] Tomaso Vairo, Mauro Quagliati, Tania Del Giudice, Antonio Barbucci, and Bruno Fabiano. From Land-to Water-Use-Planning: A Consequence Based Case-Study Related to Cruise Ship Risk. *Safety Science*, 97(8):120–133, 2017.

[114] Kambiz Mokhtari, Jun Ren, Roberts Charles, and Jin Wang. Decision Support Framework for Risk Management on Sea Ports and Terminals Using Fuzzy Set Theory and Evidential Reasoning Approach. *Expert Systems with Applications*, 39(5):5087–5103, 2012.

[115] Zahed Shahmoradi and Tonguç Ünlüyurt. Failure detection for series systems when tests are unreliable. *Computers & Industrial Engineering*, 118:309–318, 2018.

[116] Navid Ahmadian, Gino J Lim, Jaeyoung Cho, and Selim Bora. A quantitative approach for assessment and improvement of network resilience. *Reliability Engineering & System Safety*, page 106977, 2020.

[117] Mohammad Najarian and Gino J Lim. Optimizing infrastructure resilience under budgetary constraint. *Reliability Engineering & System Safety*, 198:106801, 2020.

[118] Mohammad Najarian and Gino J Lim. Design and assessment methodology for system resilience metrics. *Risk Analysis*, 39(9):1885–1898, 2019.

[119] Pedro Antão, Marlene Calderón, Martí Puig, Antonis Michail, Chris Wooldridge, and RM Darbra. Identification of Occupational, Health, Safety, Security (OHSS) and Environmental Performance Indicators in Port Areas. *Safety Science*, 85:266–275, 2016.

[120] Aline Maigret. Sustainability reporting in the port sector. *IIIEE Master thesis*, 2014.

[121] MPA Perera and B Abeysekara. Defining KPIs to Measure Eco-Sustainable Performance at Container Terminals in Sri Lanka. *Moratuwa Engineering Research Conference (MERCon)*, 2016. (pp. 315-320). IEEE.

[122] Davìd Ben-Arieh. Multi-Criteria Decision Making Methods: A Comparative Study. 2002.

[123] Mark Velasquez and Patrick T Hester. An Analysis of Multi-Criteria Decision Making Methods. *International Journal of Operations Research*, 10(2):56–66, 2013.

[124] T. L. Saaty. Analytic Network Process. 2013. (pp. 64-72). Springer US.

[125] The World Bank, 2017. Retrieved from <https://data.worldbank.org> (Accessed April 8, 2019).

[126] European Union. Environment, 2017. Retrieved from <https://europa.eu/european-union/topics/environment_en> (Accessed April 8, 2019).

[127] Anahita Molavi, Gino J Lim, and Bruce Race. A framework for building a smart port and smart port index. *International Journal of Sustainable Transportation*, pages 1–13, 2019. DOI: 10.1080/15568318.2019.1610919.

[128] AD Hawkes and MA Leach. Modelling high level system design and unit commitment for a microgrid. *Applied energy*, 86(7-8):1253–1265, 2009.

[129] T. C. Smythe. Assessing the Impacts of Hurricane Sandy on the Port of New York and New Jersey's Maritime Responders and Response infrastructure. 2013. Natural Hazards Center.

[130] T. Petermann, H. Bradke, A. Lullmann, M. Poetzsch, and U. Riehm. What Happens during a Blackout: Consequences of a Prolonged and Wide-Ranging Power Outage. 2014. BoDâĂŞ-Books on Demand.

[131] P. Mancarella and G. Chicco. Global and local emission impact assessment of distributed cogeneration systems with partial-load models. *Applied Energy*, 86(10):2096–2106, 2009.

[132] Navid Ahmadian, Gino J Lim, Maryam Torabbeigi, and Seon Jin Kim. Collision-free multi-uav flight scheduling for power network damage assessment. In *2019 International Conference on Unmanned Aircraft Systems (ICUAS)*, pages 794–798. IEEE, 2019.

[133] Mohammad Shahidehpour and Joseph F Clair. A functional microgrid for enhancing reliability, sustainability, and energy efficiency. *The Electricity Journal*, 25(8):21–28, 2012.

[134] Giuseppe Parise, Luigi Parise, Luigi Martirano, Peniamin Ben Chavdarian, Chun-Lien Su, and Andrea Ferrante. Wise port and business energy management: port facilities, electrical power distribution. *IEEE Transactions on Industry Applications*, 52(1):18–24, 2015.

[135] Louise K Turner and Frank G Collins. Carbon dioxide equivalent (co2-e) emissions: A comparison between geopolymer and opc cement concrete. *Construction and Building Materials*, 43:125–130, 2013.

[136] Etta Grover-Silva, Miguel Heleno, Salman Mashayekh, Gonçalo Cardoso, Robin Girard, and George Kariniotakis. A stochastic optimal power flow for scheduling flexible resources in microgrids operation. *Applied energy*, 229:201–208, 2018.

[137] Ramin farajififijani, Saeed Ahmadian, Saba Ebrahimi, Ehsan Ghotbi, et al. Wind farm layout optimization problem using joint probability distribution of cvar analysis. In *2019 IEEE 9th*

Annual Computing and Communication Workshop and Conference (CCWC), pages 0007–0012. IEEE, 2019.

[138] Lutz Kruschwitz and Andreas Löffler. *Discounted cash flow: a theory of the valuation of firms*. John Wiley & Sons, 2006.

[139] Amin Khodaei, Shay Bahramirad, and Mohammad Shahidehpour. Microgrid planning under uncertainty. *IEEE Transactions on Power Systems*, 30(5):2417–2425, 2014.

[140] Muni-Fed Antea Group Energy Partners, LLC and The Port of Long Beach. Microgrid Technology White Paper-Port of Long Beach, August 2016. Retrieved from <http://www.polb.com/civica/filebank/blobdload.asp?BlobID=13595> (Accessed April 15, 2019).

[141] Yiwei Wu, Masoud Barati, and Gino J Lim. A pool strategy of microgrid in power distribution electricity market. *IEEE Transactions on Power Systems*, 35(1):3–12, 2019.

[142] Eastern Research Group. 2013 Goods Movement Air Emissions Inventory, March 2017. Retrieved from <http://porthouston.wpengine.com/wp-content/uploads/2016/11/PHA-2013-GMEI-Executive-Summary-Report.pdf> (Accessed April 15, 2019).

[143] Port of Houston. Annual Report 2017 - year in Review, 2017. Retrieved from <https://porthouston.com/wp-content/uploads/82004_POHAR_FINAL-1.pdf> (Accessed April 15, 2019).

[144] Zhi Wu, Pingliang Zeng, Xiao-Ping Zhang, and Qinyong Zhou. A solution to the chance-constrained two-stage stochastic program for unit commitment with wind energy integration. *IEEE Transactions on Power Systems*, 31(6):4185–4196, 2016.

[145] EcoDesign. Solar Radiation Data: Houston, TX. Retrieved from <http://web.utk.edu/~archinfo/EcoDesign/escurriculum/CLIMATEDATA/CITYDATA/Houston/HoustonRadiation%7F.html> (Accessed April 15, 2019).

[146] World Weather and Climate Information. Average Wind Speed in Houston (Texas). Retrieved from <https://weather-and-climate.com/average-monthly-Wind-speed,houston,United-States-of-America> (Accessed April 15, 2019).

[147] LUKAS KUDUMO Siremo. Application of predictive reliability analysis techniques in distribution networks. *BSc. Eng. Thesis, Department of Electrical Engineering, University of Cape Town*, 2008.

[148] CenterPoint Energy. Reliability Indexes. Retrieved from <https://www.centerpointenergy.com/en-us/Services/Pages/reliability-indexes.aspx?sa=HO&au=bus> (Accessed April 15, 2019).

[149] Michael D McKay, Richard J Beckman, and William J Conover. Comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics*, 21(2):239–245, 1979.

[150] Aida Khayatian, Masoud Barati, and Gino J Lim. Integrated microgrid expansion planning in electricity market with uncertainty. *IEEE Transactions on Power Systems*, 33(4):3634–3643, 2017.

[151] Richard Rosenthal. GAMS: A Users Guide, 2016. GAMS Development Corporation, Washington, DC, USA.

[152] P. Zhou and M. Wang. Carbon dioxide emissions allocation: A review. *Ecological Economics*, 125:47 – 59, 2016.

[153] David Gibbs, Patrick Rigot-Muller, John Mangan, and Chandra Lalwani. The Role of Sea Ports in End-to-End Maritime Transport Chain Emissions. *Energy Policy*, 64:337–348, 2014.

[154] Dale Neef. The development of a global maritime emissions inventory using electronic monitoring and reporting techniques. In *18th Annual International Emission Inventory Conference Comprehensive Inventories-Leveraging Technology and Resources*, pages 14–17, 2009.

[155] Anahita Molavi, Jian Shi, Yiwei Wu, and Gino J Lim. Enabling smart ports through the integration of microgrids: A two-stage stochastic programming approach. *Applied Energy*, 258:114022, 2020.

[156] American Association of Port Authorities (AAPA). 2018 National Economic Impact of the U.S. Coastal Port System, 2018. <https://www.ttnews.com/articles/ports-shipping-industry-responsible-26-us-gdp-study-says>.

[157] American Association of Port Authorities. National Economic Impact of the U.S. Coastal Port System, 2019. <https://www.ttnews.com/articles/ports-shipping-industry-responsible-26-us-gdp-study-says>.

[158] TWP Smith, JP Jalkanen, BA Anderson, JJ Corbett, J Faber, S Hanayama, E O'keeffe, S Parker, L Johanasson, L Aldous, et al. Third IMO GHG Study. 2015.

[159] Hoda Davarzani, Behnam Fahimnia, Michael Bell, and Joseph Sarkis. Greening ports and maritime logistics: A review. *Transportation Research Part D: Transport and Environment*, 48:473–487, 2016.

[160] Ellen Karoline Norlund and Irina Gribkovskaia. Reducing emissions through speed optimization in supply vessel operations. *Transportation Research Part D: Transport and Environment*, 23:105–113, 2013.

[161] Feiyang Zhao, Wenming Yang, Woei Wan Tan, Wenbin Yu, Jiasheng Yang, and Siaw Kiang Chou. Power management of vessel propulsion system for thrust efficiency and emissions mitigation. *Applied energy*, 161:124–132, 2016.

[162] Dirk Steenken, Stefan Voß, and Robert Stahlbock. Container terminal operation and operations research - a classification and literature review. *OR Spectrum*, 26(1):3–49, Jan 2004.

[163] S. S. Fazeli, S. Venkatachalam, R. B. Chinnam, and A. Murat. Two-stage stochastic choice modeling approach for electric vehicle charging station network design in urban communities. *IEEE Transactions on Intelligent Transportation Systems*, pages 1–16, 2020.

[164] Nuri C Onat, Murat Kucukvar, and Shiva Afshar. Eco-efficiency of electric vehicles in the united states: A life cycle assessment based principal component analysis. *Journal of cleaner production*, 212:515–526, 2019.

[165] Devendra Singh, KA Subramanian, and SK Singal. Emissions and fuel consumption characteristics of a heavy duty diesel engine fueled with hydroprocessed renewable diesel and biodiesel. *Applied Energy*, 155:440–446, 2015.

[166] Aaron Windecker and Adam Ruder. Fuel economy, cost, and greenhouse gas results for alternative fuel vehicles in 2011. *Transportation Research Part D: Transport and Environment*, 23:34 – 40, 2013.

[167] Giorgio Zamboni, Michel Andre, Adelia Roveda, and Massimo Capobianco. Experimental evaluation of heavy duty vehicle speed patterns in urban and port areas and estimation of their fuel consumption and exhaust emissions. *Transportation Research Part D: Transport and Environment*, 35:1 – 10, 2015.

[168] M Meinert, M Melzer, C Kamburow, R Palacin, M Leska, and H Aschemann. Benefits of hybridisation of diesel driven rail vehicles: Energy management strategies and life-cycle costs appraisal. *Applied energy*, 157:897–904, 2015.

[169] Zicheng Bi, Tianze Kan, Chunting Chris Mi, Yiming Zhang, Zhengming Zhao, and Gregory A Keoleian. A review of wireless power transfer for electric vehicles: Prospects to enhance sustainable mobility. *Applied Energy*, 179:413–425, 2016.

[170] Charles D Kolstad. Empirical properties of economic incentives and command-and-control regulations for air pollution control. *Land Economics*, 62(3):250–268, 1986.

[171] Robert N Stavins. Market-based environmental policies. In *Public policies for environmental protection*, pages 41–86. Routledge, 2010.

[172] Per Kageson. *Economic instruments for reducing emissions from sea transport*. European Federation for Transport and Environment, 1999.

[173] Chul-hwan Han. Strategies to reduce air pollution in shipping industry. *The Asian Journal of Shipping and Logistics*, 26(1):7–29, 2010.

[174] Gershon Alperovich and Itzhak Weksler. A class of utility functions yielding linear demand functions. *The American Economist*, 40(1):20–23, 1996.

[175] Jean Tirole. *The theory of industrial organization*. MIT press, 1988.

[176] Mostafa Amini and Farzad Yousefian. An iterative regularized mirror descent method for ill-posed nondifferetiable stochastic optimization. *arXiv preprint arXiv:1901.09506*, 2019.

[177] Alexander Mitsos. Global solution of nonlinear mixed-integer bilevel programs. *Journal of Global Optimization*, 47(4):557–582, Aug 2010.

[178] José E Gutierrez-Romero, Jerónimo Esteve-Pérez, and Blas Zamora. Implementing onshore power supply from renewable energy sources for requirements of ships at berth. *Applied Energy*, 255:113883, 2019.

[179] R. D. Cameron. Roadmap for Moving Forward with Zero Emission Technologies at the Ports of Long Beach and Los Angeles, 2011. <`http://www.cleanairactionplan.org/documents/zero-emissions-roadmap-technical-report.pdf/`>.

[180] V. Jayaram, M. Yusuf Khan, J. W. Miller, W. A. Welch, K. Johnson, and D. R. Cocker. Evaluating Emission Benefits of a Hybrid Tug Boat, 2010.

[181] C. Mrazik, M. Baron, and A. Stabbert. A Cost Benefit Analysis of Diesel and Liquid Natural Gas for Locomotive Engines, 2015. <`http://sites.psu.edu/clm5947/wp-content/uploads/sites/33075/2015/09/Project_02_Final_Draft-2.pdf`>.

[182] Nick Sahinidis. “BARON user manual v. 2019.7.13", 2019. The Optimization Firm, LLC.

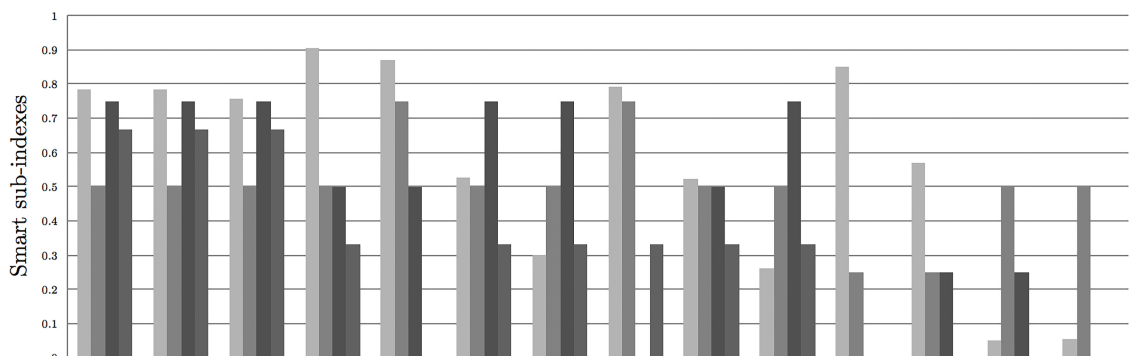
[183] Hong S Ryoo and Nikolaos V Sahinidis. Global optimization of nonconvex nlps and minlps with applications in process design. *Computers & Chemical Engineering*, 19(5):551–566, 1995.

[184] Wouter Jacobs. Port competition between los angeles and long beach: an institutional analysis. *Tijdschrift voor economische en sociale geografie*, 98(3):360–372, 2007.

[185] Port of Long Beach. Port of Long Beach: The Green Port. <`http://www.polb.com/`>.

Appendix A

Supplement for Section 3



	Port of Hamburg	Port of Rotterdam	Port of Antwerp	Port of Busan	Port of Singapore	Port of Los Angeles	Port of Vancouver	Port of Jebel Ali	Port of New york and New jersey	Port of Houston	Port of Shanghai	Port of Tanjung Priok	Port of Jeddah	Port of Hong Kong
SOI	0.786	0.784	0.755	0.904	0.871	0.525	0.301	0.794	0.523	0.261	0.850	0.570	0.052	0.055
SSSI	0.500	0.500	0.500	0.500	0.750	0.500	0.500	0.750	0.500	0.500	0.250	0.250	0.500	0.500
SEnI	0.750	0.750	0.750	0.500	0.500	0.750	0.750	-	0.500	0.750	-	0.250	0.250	-
SEgI	0.667	0.667	0.667	0.333	-	0.333	0.333	0.333	0.333	0.333	-	-	-	-

Figure A.1: Comparison of the sub-indices for 14 ports, data unavailability is marked with (-)

Table A.1: Literature review on the smart port initiatives and the related studies

Category of approach	Initiatives and studies	Description
Multipurpose Initiatives	Mediterranean Maritime Integrated Projects	Three major elements: operations, environment, and energy, 23 criteria and 68 KPIs for smartness of a port
	Hamburg Port Authority	Smart logistics: infrastructure, smart traffic flow, smart trade flow Smart energy: use of renewable energies, increasing energy efficiency, and mobility
	Port of Rotterdam	Integration of knowledge exploration and knowledge exploitation with the motto of connecting knowledge. Five road maps: future proof port infrastructure, smart energy, smart logistics, world port city, and smartest port
	Erasmus Smart Port Rotterdam	A cooperation between the Port Authority of Rotterdam and port-related scientists from Erasmus University Rotterdam, five themes: operational excellence in ports and networks, drivers for green port-related operations, governance for a sustainable port, ports in global networks, and visibility for connected port
	Port of Amsterdam	Smartly promoting growth, innovation, sustainability, use of physical space, and caring about energy and environment
Targeted Initiatives	Maritime Port Authority of Singapore	Use of mobile technology and wireless connectivity to improve communications, efficiency, and crew satisfaction: 4G broadband access, free Wi-Fi services, launch of myMaritime@SG mobile application
	Singapore Smart Port Hackathon	Discussions on innovative ideas embracing challenges in three areas: maritime services value chain, maritime logistics supply chain, and cruise/ferry terminal operations
	World Port Hackathon	Discussions on challenges in areas of infrastructure & logistics, energy & climate, disrupt the port in Rotterdam
	Port Authority of Cartagena	Adoption of Posidonia SmartPort application
	Kalmar Smart Port	Automation solutions: Smart Path, Smart Stack, Smart Lift, Smart Rail, Smart Trucks, Smart Quay, Smart Lane, Smart Fleet
	Arelsa Smart Port	Offering Smart Port solutions and services: software platform, mega yacht panels, Citiport pedestals, and Smart Port System for remote controlling and service management
	United Nations Conference on Trade and Development	Specification of smart port: ITS port, logistic community, connection to smart city and smart hinterland, providing multimodal services, and being sustainable
	European Union	Regulations on transport, energy, and ICT
	International Maritime Organization	E-navigation and conventions: MARPOL-ISPS-ISM-PSC -SECA
	Integrated Port Management System	A web-based integrated system that incorporates the logistics around the vessel traffic services, rail logistics, marine and terminal operations, and provides real-time reporting ability in the port.
	SmartPort platform	Big data analysis, visualization, and management tool for sensors' data collected in ports
	Kenya Ports Authority	Security management system and automated processes
	Smart Port Security Act	Legislation from Homeland Security regarding maritime security

Table A.2: KPIs for quantifying sub-domains in “Operations" category

Operations
1. Annual throughput (TEU/Meter of container quay)
2. Annual TEUs/Total terminal area
3. Annual TEUs/Total storage or yard area
4. Annual TEUs/Total storage or yard area plus total hinterland storage area
5. Annual TEUs/Number of container terminals
6. Annual TEUs reefers/Total number of electrical outlets for reefers (static capacity)
7. Annual throughout (tonnage/meter of container quay)
8. Annual cargo tonnage/Total terminal area
9. Annual cargo tonnage/Total storage or yard area
10. Annual cargo tonnage/Total storage or yard area plus total hinterland storage area
11. Annual cargo tonnage/Number of container terminals
12. Length of quay with +14 m depth/Total quay length
13. Annual TEUs/Capacity of the container terminals (static capacity)
14. Average annual number of hours (that container terminals are working)
15. Annual TEUs/Average annual number of hours (containers terminals are working)
16. Number of ICT that the port and terminals operators use and offer to the port community
17. Annual throughput in TEU per number of quayside cranes
18. Percentage of automatized quayside cranes
19. Annual throughput in TEU per number of yard gantries
20. Percentage of automatized yard gantries
21. Annual throughput in TEU per number of equipment for internal movements (trucks, shuttle, etc.)
22. Percentage of automatized equipment for internal movements (trucks, shuttle, etc.)
23. Total percentage of automatized quayside cranes, yard gantries and equipment for internal movements
24. Use of the intermodality-railway option (Total TEUs transported by rail/Total TEUs)
25. Use of the intermodality-road option (Total TEUs transported by road/Total TEUs)
26. Total number of TEUs/Number of carriers (only carriers of maritime transport)
27. Number of main lines (large intercontinental and inter-oceanic lines with large ships and tonnage arriving in port)/Total number of lines
28. Total TEUs per number of vessels that stop in the port
29. Total cargo tonnage per number of vessels that stop in the port

Table A.3: KPIs for quantifying sub-domains in “Environment" category

Environment
1. Number of environmental management systems based on international standards (e.g., EMAS or ISO 14001) implemented by port authority and port operators/Total number of terminal operators
2. Total hazardous wastes generated by the terminal operators disaggregated by sources per TEUs (Wastes from ships (i.e., MARPOL wastes) are not included.)
3. Total wastes collected in a selective way from all port activities (organic, plastic, paper,wood, electronics, etc.) per total port area. (Wastes from ships (i.e., MARPOL wastes) are not included.)
4. Total wastes generated that are intended to operations of reuse, recycling, and vaporization disaggregated per kind of wastes per total port area (Tons/m^2)
5. Total water consumption by all port activities per total port area (m^3/m^2)
6. Total water consumption by terminal operators per TEUs (m^3/TEUs)
7. Total water consumed by ships per vessels stops (m^3/Vessels stops)
8. Volume of water consumption that came from reuse operations (in all port area) per total volume of water consumed (%)
9. Total wastewater generated by all port activities per total port area (m^3/m^2)
10. Total wastewater generated by the terminal operators per TEUs (m^3/TEUs)
11. Total volume of wastewater from all port activities that are treated for reuse per total volume of wastewater in the port (%)
12. Port activities covered by environmental management systems (%)
13. Number of waste management plans implemented by port authority and port operators / Total number of terminal operators
14. Port activities covered by waste management plans (%)
15. Total wastes generated by all port activities (Tons). Wastes from ships (i.e., MARPOL wastes) are not included per total port area
16. Total wastes generated by terminal operators per TEUs (Tons/TEUs). The wastes from ships (i.e., MARPOL wastes) are not included.
17. Total wastes generated by ships (MARPOL wastes) disaggregated per kind of wastes and per vessels stops (Tons/Vessels stops)
18. Total hazardous wastes generated by all port activities disaggregated by sources per total port area. Wastes from ships (i.e., MARPOL wastes) are not included. (CO2 equivalents Tons/m^2)
19. Lden - noise pollution
20. Lnight - noise pollution
21. Total leaks and spills (Tons) of polluting substances at sea per vessels stops
22. Number of monitoring systems to assess water quality (temperature, salinity, fecal coliform, etc.) in port area per total quay berth
23. Number of monitoring systems to assess air quality in port area per total port area
24. Greenhouse gas emissions from all port activities per total port area
25. Total annual GHG emissions per TEU
26. Total annual air emission
27. Amount of recycled waste

Table A.4: KPIs for quantifying sub-domains in "Energy" category

Energy
1. Total energy consumption (primary energy) by port authority per total port area (kWh/m^2)
2. Total energy consumption (primary energy) by the container terminals per total terminal area (kWh/m^2)
3. Total energy consumption (primary energy) per container per total TEUs (kWh/TEU)
4. Total energy consumption (primary energy) by reefers per Total number of reefer TEUs (kWh/Reefer TEU)
5. Total energy consumption (primary energy) by internal fleet per terminal area (kWh/m^2)
6. Total energy consumption (primary energy) by office buildings per terminal area (kWh/m^2)
7. Total energy consumption (primary energy) by lighting system (port terminal area, not office buildings) per terminal area (kWh/m^2)
8. Total energy consumption (primary energy) by the terminals' equipment per total number of TEUs (kWh/TEU)
9. Total energy consumption (primary energy) by the terminals' equipment per total terminal area (kWh/m^2)
10. Total energy consumption (primary energy) by cranes per total number of cranes (kWh/crane)
11. Percentage of heating fuels from renewable resources managed by the port authority
12. Percentage of heating fuels from renewable resources managed by terminal operators
13. Percentage of energy from renewable resources managed by port authority
14. Percentage of energy from renewable resources managed by terminal operators
15. Number of energy management certificates or arrangements according to any standard (ISO 50001, etc. (by port authority and terminal operators)/Total number of terminal operators
16. Port activities covered by energy management systems (%)
17. Energy saved due to conservation and efficiency improvements

Table A.5: KPIs for quantifying sub-domains in “Safety & Security" category

Safety & Security
1. Number of safety and security arrangements and certificates
2. Scope of the safety and security arrangements and certificates (port activities covered by the safety and security management systems)
3. Annual number of nautical accidents (significant or incidents in areas under the jurisdiction of the port authorities)
4. Number of failures to comply (port regulations, industry safety standards, etc.)
5. Number of spills (nautical or industrial)
6. Number of fires and explosions (nautical or industrial)
7. Number of foundering
8. Investment in safety
9. Number of port security incidents (different types of breaches-e.g., access without authorization, thefts and claims, jobs without authorization, etc.)
10. Number of security drills
11. Investment in protection (maintenance and investment)
12. Compliance with ISPS requirements
13. Percentage of employees trained in the organization’s anti-corruption policies and procedures
14. Number of Security meetings (police forces and authorities, private security and technological measures firms, shipping companies, shipping agents, and foreign consulates)
15. Number of port security inspections