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ENERGY MANAGEMENT AND OPERATION OPTIMIZATION OF SEAPORT MICROGRIDS

BY
NUR NAJIHAH BINTI ABU BAKAR

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AALBORG UNIVERSITY
DENMARK

Energy Management and Operation Optimization of Seaport Microgrids

Ph.D. DISSERTATION

by

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AALBORG UNIVERSITY
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Curriculum Vitae

Nur Najihah Abu Bakar received a Bachelor of Engineering in Electrical in 2012 and a Master of Engineering in Electrical in 2015 from Universiti Teknologi Malaysia (UTM), Johor. She has worked as a lecturer at Universiti Malaysia Perlis (UniMAP) since 2015. Currently, she is pursuing her Ph.D. degree at the Center for Research on Microgrids (CROM), AAU Energy, Aalborg University, Denmark. Her research specializes in the port operation optimization and energy management of seaport microgrids with shore power systems of cold ironing.

Abstract

The emissions of the maritime sector caused by ship transportation and other fossil fuel sources pose a threat to the environment and human health. It drives an increasing interest in adopting electrification solutions to revolutionize the conventional maritime energy-intensive and highly polluting industry. Accordingly, this thesis is one of the pioneering attempts to implement a seaport microgrid and carbon capture shore power system of cold ironing at a port dedicated to sustainability while remaining competitive.

However, the technological and research gaps of the conventional port scheduling paradigm constitute challenges in a synergy between the two prominent maritime electrification systems of seaport microgrids and cold ironing. The incorporation of cold ironing into seaport operations introduces new challenges to handling workflow and the potential impact of such integration has not yet been quantitatively addressed. Developing strategic management to improve port performance is always an issue for the port operators. This research gap motivated this study to develop an integrated operation and energy management framework by executing forecasting and optimization techniques for coordinating these technologies toward the emission neutrality goal.

This thesis begins with an extensive review of the significant aspects of cold ironing technology and seaport microgrids. A range of factors associated with the varying demand for cold ironing in seaport microgrids, requiring advanced forecasting techniques, are described in Chapter 2. Another challenge is that the integration of cold ironing with limited capacities increases the complexity of the existing seaside operation at port namely the berth allocation problem (BAP) and quay crane allocation problem (QCAP). It prolongs the waiting time for the ships to be served at berth. Thus, a seaside operational optimization model is developed in Chapter 3 to cooperatively schedule BAP, QCAP, and cold ironing assignment problems (CIAP). Chapter 4 integrates bilevel optimization as an energy management system (EMS) framework to coordinate the joint cold ironing with the seaport microgrid concept, providing more flexibility in energy scheduling while remaining cost-effective. Finally, Chapter 5 presents the overall conclusions of the thesis, research contribution, and future recommendations.

Dansk Resumé

Emissionerne fra den maritime sektor forårsaget af skibstransport og andre fossile brændstoffer udgør en trussel mod miljøet og menneskers sundhed. Det driver en stigende interesse for at indføre elektrificeringsløsninger for at revolutionere den konventionelle maritime energiintensive og stærkt forurenende industri. Derfor er denne afhandling et af de banebrydende forsøg på at implementere et havhavns mikronet og kulstoffangst landstrømsystem til koldstrygning i en havn dedikeret til bæredygtighed, mens den forbliver konkurrencedygtig.

Imidlertid udgør de teknologiske og forskningsmæssige huller i det konventionelle havneplanlægningsparadigme udfordringer i en synergi mellem de to fremtrædende maritime elektrificeringssystemer, søhavns mikronet og koldstrygning. Inkorporeringen af koldstrygning i havneoperationer introducerer nye kompleksitetsudfordringer til håndtering af havnedriftsarbejdsgange, og den potentielle virkning af en sådan integration er endnu ikke blevet behandlet kvantitativt. Udvikling af strategisk ledelse for at forbedre havnens ydeevne er altid et problem for havneoperatørerne. Dette forskningsgab motiverede denne undersøgelse til at udvikle en integreret drifts- og energistyringsramme ved at udføre prognose- og optimeringsteknikker til at koordinere disse teknologier mod målet om emissionsneutralitet.

Afhandlingen indledes med en omfattende gennemgang af de væsentlige aspekter af koldstrygeteknologi og søhavns mikronet. En række faktorer, der påvirker den dynamiske belastning af koldstrygning i søhavns mikronet, hvilket nødvendiggør avancerede prognoseteknikker, er beskrevet i kapitel 2. En anden udfordring er, at integrationen af koldstrygning med begrænset kapacitet øger kompleksiteten af den eksisterende søsidedrift i havnen, nemlig kajtildelingsproblemet (BAP) og kajkrantildelingsproblemet (QCAP). Det forlænger ventetiden på, at skibene skal betjenes ved kaj. Der er således udviklet en operationel optimeringsmodel ved havet i kapitel 3 til i fællesskab at planlægge BAP-, QCAP- og koldstrygningsproblemer (CIAP). Kapitel 4 integrerer bilevel-optimering som en energistyringssystem (EMS)-ramme for at koordinere den fælles koldstrygning med seaport microgrid-konceptet, hvilket giver mere fleksibilitet i energiplanlægning, mens det forbliver omkostningseffektivt. Endelig præsenterer kapitel 5 afhandlingens overordnede konklusioner, forskningsbidrag og fremtidige anbefalinger.

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Finally, I am grateful to all my colleagues and friends from the CROM group. Your boundless energy and relentless pursuit of excellence have motivated me toward this successful journey. Special dedication to Dr. Muzaidi and Dr. Nor Baizura, who inspired me and encouraged me to pursue my studies in AAU with the CROM group. This journey is valuable, beautiful, wonderful, and one of the great moments in my life.

Sincerely,
Nur Najihah Binti Abu Bakar
AAU Energy, Aalborg University
March 2024.

Publications

Several significant outputs of the dissertation research have been published or submitted in peer-reviewed scientific international journals. Additionally, a few doctoral studies have been presented at international conferences. The body content of this thesis comprises the subsequent papers:

1. **N. N. Abu Bakar**, N. Bazmohammadi, J. C. Vasquez, And J. M. Guerrero, “Electrification Of Onshore Power Systems In Maritime Transportation Towards Decarbonization Of Ports: A Review Of The Cold Ironing Technology,” *Renewable and Sustainable Energy Reviews*, Vol. 178, P. 113243, 2023, Doi: 10.1016/J.Rser.2023.113243 [1].

2. **N. N. Abu Bakar**, N. Bazmohammadi, H. Çimen, T. Uyanik, J. C. Vasquez, And J. M. Guerrero, “Data-Driven Ship Berthing Forecasting For Cold Ironing In Maritime Transportation,” *Applied Energy*, Vol. 326, P. 119947, 2022, Doi: 10.1016/J.Apenergy.2022.119947 [2].

3. **N. N. Abu Bakar**, J. M. Guerrero, J. C. Vasquez, N. Bazmohammadi, Yun Yu, A. Abusorrah, Y. A. Al-Turki, “A Review Of The Conceptualization And Operational Management Of Seaport Microgrids On The Shore And Seaside,” *Energies*, Vol. 14, No. 7941, Pp. 1–31, 2021, Doi: Https://Doi.Org/10.3390/En14237941 [3].

4. **N. N. Abu Bakar**, J. M. Guerrero, J. C. Vasquez, N. Bazmohammadi, M. Othman, B.D. Rasmussen, Y. A. Al-Turki, “Optimal Configuration And Sizing Of Seaport Microgrids Including Renewable Energy And Cold Ironing – The Port Of Aalborg Case Study,” *Energies*, Vol. 15(2), P. 431, 2021 [4].

5. **N. N. Abu Bakar**, N. Bazmohammadi, Y. Yu, J. C. Vasquez, And J. M. Guerrero, “Environmental Dispatch Strategies For Onshore Power Systems,” In *Iecon 2022-48th Annual Conference Of The Ieee Industrial Electronics Society*, 2022, Pp. 13–16 [5].

6. **N. N. Abu Bakar**, J. M. Guerrero, N. Bazmohammadi, And J. C. Vasquez, “Optimal Berth Allocation In Ports With The Deployment Of Shore To Ship Power System,” In *2022 Ieee International Conference On Power And Energy (Pecon)*, 2022, Pp. 263–268 [6].

7. **N. N. Abu Bakar**, T. Uyanik, Yasin Arslanoˇglu, J. C. Vasquez, and J. M. Guerrero, "Two-Stage Energy Management Framework of The Cold Ironing Cooperative with Renewable Energy for Ferry," *Under review by the Journal of Energy Conservation and Management*, submitted on 30/10/2023.

8. **N. N. Abu Bakar**, N. Bazmohammadi, J. C. Vasquez, and J. M. Guerrero, "Cooperative Scheduling of Berth Allocation, Cold Ironing, And Quay Cranes Assignment at Seaport Terminals," *Under review by the Journal of Heliyon,* submitted on 12/02/2024.

9. **N. N. Abu Bakar**, N. Bazmohammadi, J. C. Vasquez, and J. M. Guerrero, "Energy management system for electrified seaside port operations with integrated cold ironing and seaport microgrid," *Under review by the Journal of Applied Energy,* submitted on 08/02/2024.

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Part I

Extended Summary

Acronyms

ANN	Artificial neural network
BAP	Berth allocation problem
CIAP	Cold ironing assignment problems
CO2	Carbon dioxide
ESPO	European Sea Ports Organisation
EMS	Energy management system
EV	Electric vehicle
GAMS	General algebraic modeling system
IMO	International Maritime Organization
KPI	Key performance indicators
NOx	Nitrogen oxides
MAE	Mean absolute error
MDO	Marine diesel oil
MG	Microgrid
MLR	Multiple linear regression
MSE	Mean square error
PCC	Point of Common Coupling
PM	Particulate matter
PMS	Port management system
QCAP	Quay crane allocation problem
RMSE	Root Mean Square Error
SO2	Sulfur dioxide

Chapter 1. Introduction

1.1. Motivation

The maritime sector comprises a broad system with interconnected domains, consisting of energy networks, operations, technologies, logistics, communication, legislation, and management. The smooth cooperation between them enables the efficient global flow of goods and services. The escalating competence of marine operations in maintaining a balance between innovation and compliance across various maritime regulations presents ongoing problems as well as opportunities. Industry stakeholders must engage in collaboration for solutions to optimize performance and adapt to emerging trends in a constantly changing environment.

One of the great challenges in this industry is to fulfill the port legislation. The adoption of strict environmental policies for port activities necessitates innovative technological and managerial solutions. Accordingly, the focus of integrated technology in this research is the shore power of the cold ironing and seaport microgrid. Its execution enables cleaner energy usage at the port but also introduces new port resources, which disrupts the present way of port operation as well as energy handling. Implementing such technologies within tight operational and financial constraints risks conflicting solutions and degrading service quality without advanced port management.

Strategic coordination between operations and energy control is required for ports to remain competitive while integrating green technologies in an economically viable manner. Although extensive research exists on the port sector, focused study on all-inclusive integration challenges is limited. This gap motivates this study to propose an integrated operational and energy management framework for incorporating electrification technologies into port operations. By bridging technological, operational, economic, and sustainability considerations, this framework aims to provide structured guidance for ports undertaking green modernization. The maritime industry's environmental and competitive pressures demand such systemic solutions to enable clean, efficient, and adaptive port capabilities.

1.2. Maritime sector background

1.2.1. Introduction to seaports

Seaports are strategically located between sea and land and serve as crucial interfaces for both maritime and land transportation. Ports provide vital infrastructure linking oceangoing ships and inland distribution systems, facilitating the movement of cargo and passengers. They play a substantial role in the industrial sector, contributing to economic and social development worldwide. Ports can be categorized as local, national, and international based on their characteristics as summarized in Table 1.1. Local ports focus on regional trade and transportation, while those with national significance handle domestic cargo and passenger flows. International ports serve as global hubs connecting varied worldwide origins and destinations.

The roles of ports have undergone extensive transformations in parallel with global development, as illustrated in Fig. 1.1. Early ports in the 1960s were solely concentrated on transportation operations, without integrating trade or commercial endeavors. Subsequent generations witnessed advancements in technology, networking, international trade, and logistics. The current, fifth-generation ports are evolving into smart ports, characterized by automation, advanced technologies, intelligent infrastructure, and efficient energy management systems.

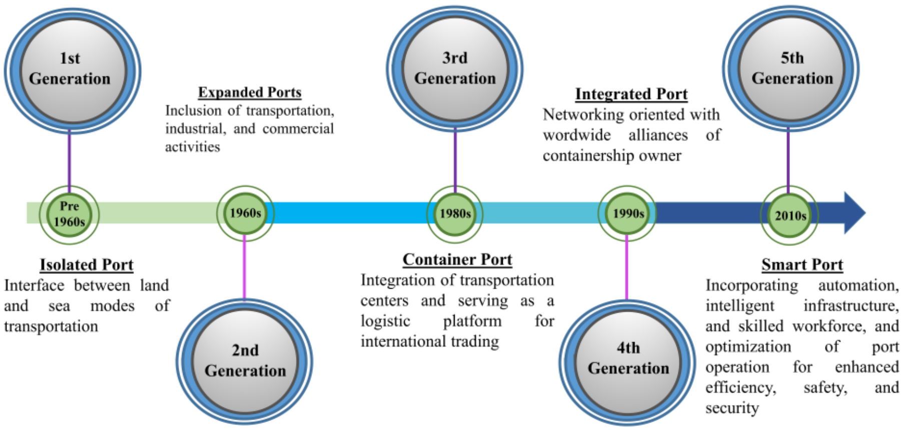


Fig. 1.1. Seaport evolution over time.

Table 1.1. Type of ports and their features [7].

Port type	Descriptions
Local port	▪ Covers a need in the local area. ▪ Limited capacity and area. ▪ Relatively small in size. ▪ No service for logistics-related operations. ▪ Not providing cruise ship operation. ▪ Yachts, boats, and small ships carrying fewer than 500 passengers are among the visiting ships.
National port	▪ Handles the demands of the nation. ▪ A medium-sized port ▪ Including small logistical and cruise activities for every kind of ship. ▪ Involved with medium-sized ships with less than 2,500 people, packages for cargo, and trucks for logistics.
International port	▪ Fulfills demands on a global scale. ▪ Biggest in size. ▪ Establish a massive logistical infrastructure. ▪ Cruise ships with over 2,500 passengers, cargo ships, container ships, various machinery, and RTG cranes.

1.2.2. Key challenges in seaports

The pressing demand for greater efficiency across maritime operations necessitates coordinated planning to optimize interconnected subsystems. To design the solution, it is essential to identify the crucial issues of the ports and recognized the areas for improvement. Fig. 1.2 outlines the ports' main challenges and Fig. 1.3 shows the identified top five priorities in the port industry from 2009 to 2023 issued by the European Sea Ports Organisation (ESPO) [8]. Accordingly, the key concerns in the maritime sector are highlighted as follows:

Economical: The maritime industry is profoundly impacted by economic factors ranging from capital costs, operating expenses, trade affordability, infrastructure investments, technological upgrades, labor, and regulatory compliance. Economic efficiency influences global trade attractiveness, where be able to lower shipping costs will attracting more shipping lines. Besides, port also obliged to comply with strict regulation that periodically change. Implementing technological advancements to meet port legislation requires large upfront expenses, even with potential long-term gains. Massive investments in ships and infrastructure coupled with highly volatile fuel prices, labor, maintenance, and rates tied to economic cycles, make cost control vital for competitiveness and survival in this cost-sensitive sector.

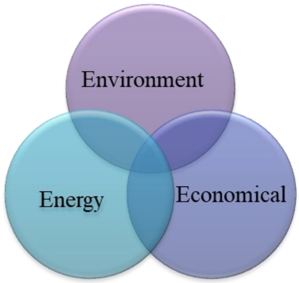


Fig. 1.2. Key challenges in the port.

	2009	2013	2019	2020	2021	2022	2023
1	Noise	Air quality	Air quality	Air quality	Air quality	Climate change	Climate change
2	Air quality	Garbage/ Port waste	Energy consumption	Climate change	Climate change	Air quality	Air quality
3	Garbage/ Port waste	Energy consumption	Climate change	Energy efficiency	Energy efficiency	Energy efficiency	Energy efficiency
4	Dredging operations	Noise	Noise	Noise	Noise	Noise	Noise
5	Dredging operations	Ship waste	Relationship with local community	Relationship with local community	Relationship with local community	Water quality	Water quality

Fig. 1.3. European Sea Ports Organisation (ESPO) report on top 5 port priorities from 2009 to 2023 [8] (Accessed on 30 January 2024).

Energy at ports: The energy aspect of port operations encompasses both the generation of energy and the consumption of energy. Ports operations are divided into several areas, including seaside, shoreside, and gate areas. Each division is utilized for different types of activities, logistics, equipment, and heavy machinery, all of which contribute to varying energy demands. Table 1.2 shows port-related operations and associated load. Accessing the generation capacity and potential consumption is vital to ensure an adequate power supply. Given the diverse appliances and activities within the marine ports, it is evident that the seaport sector has a substantial energy demand. A reliable power system is essential to provide sufficient energy to all distribution loads, as any shortfall in energy delivery can significantly disrupt seaport operations. Optimizing port energy flows in both generation and consumption with an integrated energy management strategy is the solution to flawless operations.

Table 1.2. Seaport services, assets, and loads [9],[10].

Services	Assets	Factors impacting energy usage
Ship	Passenger ships (cruise, ferry), electric ships, hovercraft, container ships, gliders, bunkers, tugs, boats, tankers, submarines, yachts, sailboats	Ship dimensions, onboard activities, operational duration, weather conditions, sea waves, and speed.
Cargo handling	Cargo, quay, storage, logistics, freight forwarder, container, loading-unloading, customs warehouse, security	Number of cranes, cargo volume, operational hours
Administration	Management and administrative building, planning, service solution, IT, monitoring	Type of electrical equipment, weather, building material, hours of operational hours, occupant behavior
Transportation	Electric vehicles, cranes, trucks, yard tractors, trains	Quantity of transportation, consumption duration
Electric Facility	Cold ironing, charging station for electric vehicles	Berthing duration, number of ships per berthing, size, and shipboard load
Maintenance	Repair and maintenance services	Type of maintenance

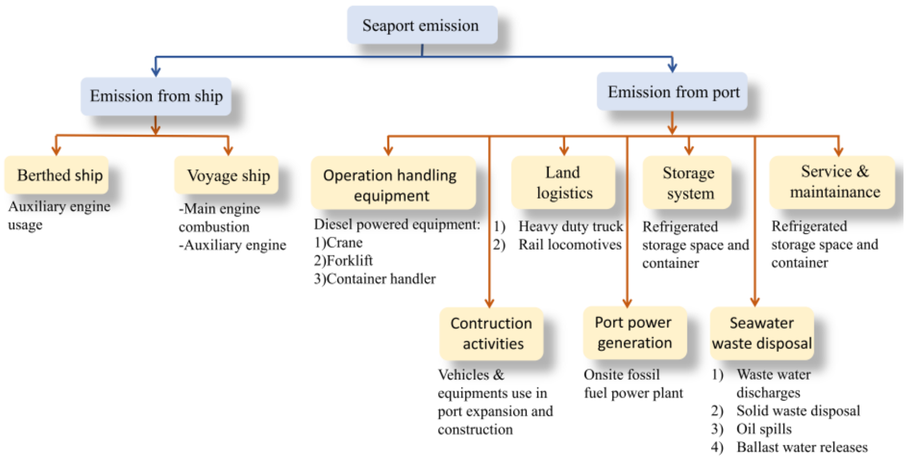


Fig. 1.4. Breakdown of emission sources at port.

Table 1.3. Adjustment in Fuel Sulfur Limit

Date	Sulfur limit in fuel [%*m/m*]	
	SO_x ECA	Global
2000	1.5	4.5
2010	1.0	4.5
2012	1.0	3.5
2015	0.1	3.5
2020	0.1	0.5

Source: Marpol 2018, Marpol Annex VI

Table 1.4. Green maritime legislation in different nations.

Country	Legislation
EU	Classification Societies – Regulation (EC) No 391/2009, Ship-Source Pollution – Directive 2000/59/EC, Marine Equipment – Directive 96/98/EC and Directive 2014/90/EU
New Zealand	Resource Management (Marine Pollution) Regulations
Australia	Environmental Protection Act 1986 (WA)
Singapore	Environmental Protection and Management Act (Cap.94A)
USA	Diesel Emission Reduction Act (DERA)

Environmental challenges at ports: The ESPO report in Fig. 1.3 highlights that the environmental problem at the ports arises from polluted air quality, noise, dredging disposal, water quality, port waste, and climate change from the conducted port activities. Additionally, the primary forms of energy consumed in this industry are generated from the combustion of polluted sources (coal and oil). The extensive use of fossil fuels in marine transportation and various port operations produces hazardous gases in the air. To make it worse, the rising worldwide demand for logistics services has led to surging maritime traffic volumes that consequently increase the pollution from their activities. This highlights the urgency of environmental concerns facing the port sector, necessitating immediate action. If left unaddressed, emissions from maritime transportation are forecasted to soar up to 250% in 2050 compared to 2012 levels [11].

Environmental management plans and regulatory measures, such as those set by the International Maritime Organization (IMO) also play a role in mitigating emissions from port activities. The port authorities have applied strict green policies such as the sulfur usage policy by IMO that keeps reducing the sulfur limit over time as can be seen in Table 1.3. New laws governing port growth and development with tighter environmental requirements are periodically introduced at both the international and domestic levels to protect the environment and waterways. This governs fundamental port operations and procedures according to their effects on the environment. Table 1.4 outlines port-related legislation in several countries that address environmental concerns.

Despite its numerous advantages in improving the environment, there are hurdles associated with complying with the policy as it involves with execution of new technology, potentially disrupting existing operations, requires high financial resources, and is time-consuming. Efforts to reduce emissions from the maritime sector include the use of cleaner energy sources in port operations, the adoption of energy-efficient technologies, retrofitting to electrified solutions, and the implementation of emission control technologies. The progressive efforts and initiatives implemented by ports worldwide driven by tightening regulations demonstrate a paradigm shift toward greater electrification. While fully electrified ports remain an aspiration for the future, the clear trajectory of current regulations and technological advances makes next-generation fully electrified ports inevitable.

1.3. Electrification solutions for the next generation ports

The emerging trend of maritime sector electrification is driven by sustainable goals with pursuing more efficient, greener solutions and technological advances. Electrification of ports refers to the transition from fossil-fuel-based equipment/infrastructure to new technologies powered by electricity. A visualized perspective of future ports with full electrification is depicted in Fig. 1.5. Research in [12] emphasizes the positive environmental impact of electrification initiatives, that play a crucial role in reducing air pollution and contributing to both local and global decarbonization efforts.

However, it is a long-term transition requiring significant investments, policy support, technological innovation, and operational changes. While large-scale electrification is challenging, it is possible to be implemented gradually and progressively over time. Additionally, ongoing research continues to address issues and refine strategies, which positions electrified ports as a vital action toward realizing a sustainable maritime sector. Motivated by this green directive, this Ph.D. work investigates the integration of two most prominent maritime electrification solutions which are:

1) Cold ironing
2) Seaport microgrid system

This research attempts to provide insights into how the maritime industry can maintain its competitiveness while grasping its commitment to sustainability through electrification.

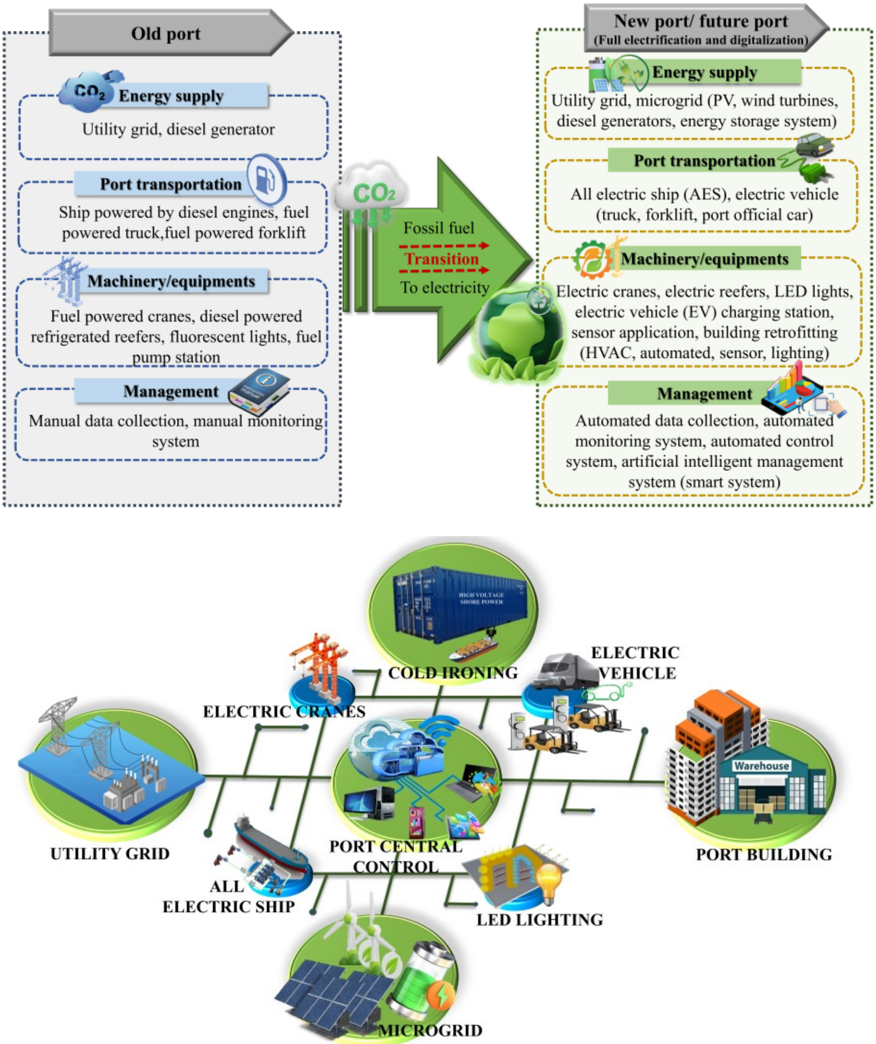


Fig. 1.5. The transition from fuel-based to electrified ports.

1.3.1. The shore power system of cold ironing

1.3.1.1 Cold ironing application in the maritime sector

The shore power system, commonly referred to as cold ironing, represents a significant electrification revolution in the maritime sector that benefits the ship transportation. Cold ironing is also recognized by various other terms including alternative shore-to-ship power (S2SP), maritime power (AMP), shore-side electricity (SSE), onshore power supply (OPS), and shore-side power (SSP) [13]–[17]. In

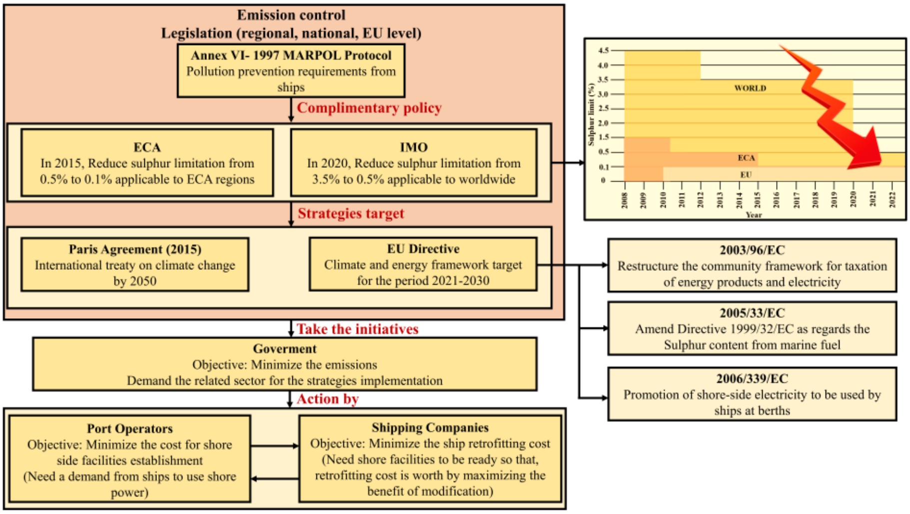


Fig. 1.6. The enforcement of cold ironing integration by port emission control legislation.

conventional practices, the ships' onboard load such as lighting, crew space, heating, and ventilation was powered by polluting auxiliary engines. The ships' generators burn huge quantities of low-quality fuels like marine diesel, gas oil, and heavy fuel oil. They result in various detrimental environmental impacts, including exhaust fumes, noise, vibrations, and air emissions during the period when the ships stay at the port, affecting port workers, onboard personnel, communities, and residents in the proximity of the port area [18].

The escalating volume of global trading activities has led to a higher dependence on ship transportation consequently increasing ship emissions. Seaborne trade statistics between 1990 and 2020 demonstrate a significant upward trajectory, with the global volume of goods loaded at ports escalating to nearly triple the 1990 levels [19]. The cold ironing mechanism makes it attainable to convert from diesel engines of ships' generators to shore-supplied electricity when ships are docked at port, eliminating gas emissions. Besides, shore power systems can mitigate noise and vibration pollution from ships. Moreover, given the transformative trend of ships moving towards all-electric ships (AES), the necessity of charging infrastructure becomes imperative, highlighting the importance of cold ironing for ports worldwide.

Cold ironing integration emerges as a pivotal initiative aligning with the worldwide pursuit of green, zero-emission ports. Concurrently, the implementation of such systems is being propelled by regulatory mandates that periodically enforce stricter sulfur control measures, compelling the maritime industry to adopt cold ironing applications. Fig. 1.6 shows the directive from the legislative bodies for the cold ironing plan of action.

The recent regulation by the IMO restricting sulfur content in fuel to 0.1%, down from 4.5% in 2000, further emphasizes the need for cold ironing [3]. This is because the desulfurization process entails high expenditures and low sulfur fuel oil usage is not still cost-effective [20]. Thus, it is foreseeable that cold ironing may soon become mandatory at all ports worldwide.

1.3.1.2 Cold ironing structure

The operational principle of cold ironing involves transferring a docked ship's power supply from its auxiliary engines to shoreside electricity from the local grid via a cable connection. This provides the energy needed for onboard electrical loads during port stay. It requires matching shoreside power supply voltages and frequencies to the berthed ship's requirements.

Fig. 1.7 shows the fundamental components of the system and its topology are classified into three clusters: centralized AC, distributed AC, and distributed DC as illustrated in Fig. 1.8 [21]–[25]. The cold ironing infrastructure comprises three main segments: the shore-side power supply, the cable connection, and the ship-side infrastructure for receiving electricity. The transformer steps down the high voltage from the utility grid, and the frequency converter aligns the frequency with the ship's specified frequency (either 60 Hz or 50 Hz) [4]. The shore-side connections include low voltage supply connection (LVSC) and high voltage supply connection (HVSC), with HVSC offering flexibility for different ships with varying voltage levels.

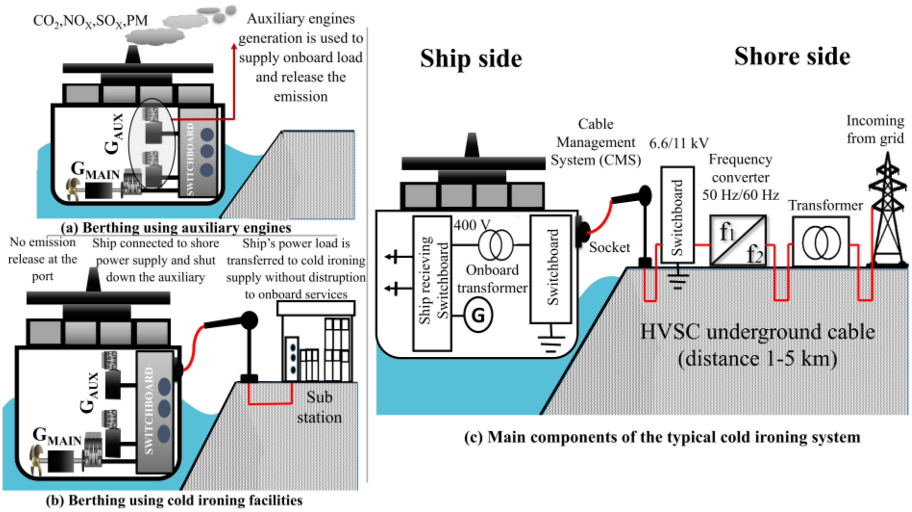


Fig. 1.7. The system components and structure of the cold ironing.

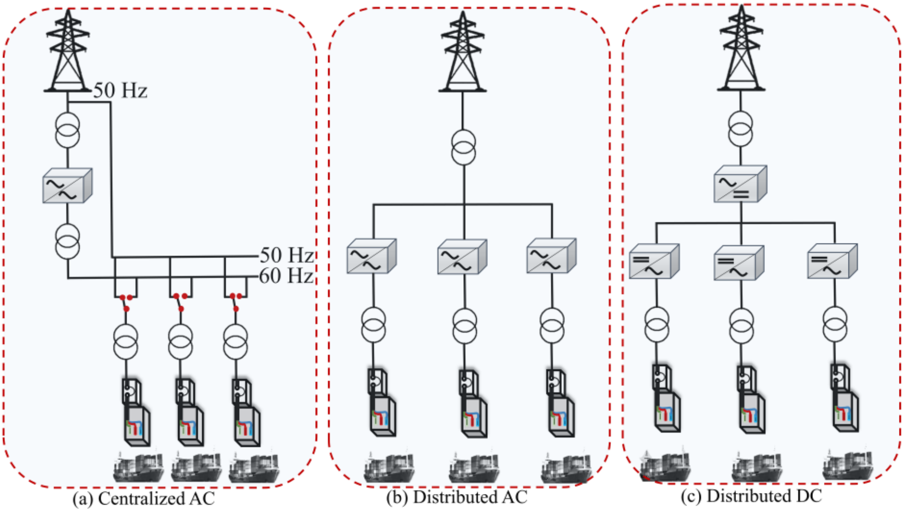


Fig.1.8. Commonly system topology employed in cold ironing.

1.3.1.3 Cold ironing power requirement

The power consumption of cold ironing is greatly associated with the activities of its main consumer, which is ship transportation. Assessing its power requirements is crucial in planning and operational management to minimize unnecessary costs. Load profiling during planning identifies facility sizing and specifications. After establishment, the load profile informs the port operational management system to enable the optimal and economical utilization of the facilities. Therefore, investigating the ships' load is essential for comprehending cold ironing's power usage.

Table 1.5. The load factor value for different types of ships [26],[27],[28].

Ship type	Cruise	Maneuver	Berthing
Container	0.13	0.5	0.17
Bulk carrier	0.17	0.45	0.22
General cargo	0.17	0.45	0.22
Roro	0.15	0.45	0.3
Oil tanker	0.13	0.45	0.67
Cruise/ passenger	0.80	0.8	0.64

Determining cold ironing demand poses challenges given the diverse ship types and their varying loads. Cruise ships, for instance, have substantial hoteling loads related to passenger services, while container ships require power for cargo handling machinery. According to the data extracted from [26], the peak power demand for a single ship can reach up to 11 MW. With limited access to actual load data, many studies estimate auxiliary consumption using a load factor reflecting the energy needed from shoreside when docked. The load factor accounts for differences across ship types to approximate overall cold ironing demand. Table 1.5 categorizes collective load factor uses in different studies, sorted by types of ship and operation modes. A load factor of 1.0 signifies that a ship is operating at 100% of its auxiliary power capacity to meet onboard electricity demands. For other load factor values below 1.0, the value represents the fraction of total auxiliary capacity being utilized by that particular ship type during specific operating modes like cruising, maneuvering, or berthing. Fortunately, numerous ports are embracing digital methods for data storage, and it is foreseeable that easily accessible data will become more prevalent in the future.

1.3.1.4 Environmental impact and economical assessment for cold ironing

Despite being employed by a few ports globally, cold ironing is considered underutilized due to its high initial costs for shoreside's facility setup and ship power receiver retrofitting, along with unclear benefits for the parties involved. In this section, two key assessments in cold ironing integration are introduced and discussed.:

Environmental impact assessment: The main harmful gases emitted by ship generators include sulfur dioxide (SO_2), nitrogen oxides (NOx), carbon dioxide (CO_2), and particulate matter (PM) [29]. The primary source of greenhouse gases leading to global climate change is CO_2, while SO_2, NOx, and PM are fatal to human health [30]. Given the primary goal of cold ironing is to minimize emissions during berthing, a comprehensive emission investigation is essential to understand the true extent of emissions from ships at the port and the cold ironing maximum capability for emission reduction. The evaluation should focus on key components, especially auxiliary engines, and consider various parameters, including:

1) Auxiliary power
2) Ships' load factor
3) Duration of berthing
4) Type of fuel used (HFO/MDO/MGO)
5) Emission coefficients

Quantifying these factors enables accurately assessing auxiliary engine emissions during port stays. Evaluating the environmental impact of cold ironing requires comparing emissions from shoreside electricity generation to emissions from ships' auxiliary engines while at berth. Most research on cold ironing's effectiveness in reducing emissions considers local grid emissions as the baseline for comparison. This comparative analysis helps determine the potential emissions reduction capability of implementing cold ironing systems.

Economical assessment: The economic challenge of high upfront costs causes investor hesitation, posing a significant barrier to the widespread adoption of cold ironing. Investors such as port operators and ship owners are cautious due to upfront costs, long payback periods, and uncertain returns. Therefore, analyzing the cost distribution between ports and ships, along with a comprehensive cost-benefit analysis is needed.

Port operators prioritize capital cost savings and revenue prospects in their decision-making and the financial benefits will justify the investment. Additionally, minimizing cold ironing operation costs is important for offering competitive energy prices to attract shipping lines. From the shipping lines' perspective, retrofitting costs, operational expenses, and electricity purchasing costs from the shore are key considerations. Ship owners prioritize minimizing costs and maximizing revenues, with retrofitting costs being a significant factor in adopting cold ironing services [31]. Interest in ship retrofitting increases when the technology ensures economic advantages while complying with environmental restrictions during berthing. Accordingly, cold ironing faces interlinked cost hurdles for ports and ships. Analyzing the cost breakdown and benefits for both stakeholders is essential to tackle the economic barriers hindering widespread technology adoption.

To optimize the cost-effectiveness of cold ironing implementation, it is important to identify and prioritize ships with longer average handling periods [32]. Ports with ships that have long berthing hours stand to benefit more from the shore power system, as it effectively reduces emissions from auxiliary engines over prolonged stay periods. Container ships, characterized by long berthing durations of 21 hours or more, have been prominent users of cold ironing systems in current implementations [22].

1.3.1.5 Challenges for cold ironing system integration

The system application complexity arises from the range of ship classes with varying energy needs, dynamic port calls, irregular duration of ship stay, and uncertainties about the accessibility of local energy supplies. These factors create challenges in coordinating cold ironing operations, leaving room for improvement that requires further investigation. This includes:

Volatile power demand: Since cold ironing electricity consumption fluctuates based on the characteristics of berthed ships, identifying the factors influencing ships' power demand is crucial to minimize uncertainties and ensure operationally efficient ports. Several potential aspects that may impact cold ironing load include berthing duration, ship traffic, and ship size. However, additional influencing factors likely exist but remain unidentified. Further analysis is required to determine the strongest correlations between different influencing parameters and ships’ power demand patterns. High accuracy of quantification of load variability factors will enable better estimation of electricity needs and is essential for strategic energy management.

Operation coordination: The integration of electrification technology in port operations brings about operational complication that disrupting conventional resource scheduling. The growing demand for shore power can lead to competition for cold ironing-enabled berths, causing delays and inefficiencies in berth allocation, thereby impacting overall port performance. To mitigate this hurdle and maintain port performance, optimized coordination between operations scheduling and energy management is necessary. Port operators need solutions to adapt to cold ironing technology while minimizing disruptions to current berth allocation practices.

Adequacy of power supply: The frequent arrival and departure of ships creates dynamic cold ironing loads at ports. Fluctuating loads from changing berth occupancy and ship power needs can pressure the ports' power supply. Especially when the larger ships under the high voltage ship category can demand up to megawatts level of power. Port also poses an energy challenge due to the uncertain peak demand during high ship traffic arrival. Thus, the application of cold ironing at the port will further increase the existing power demands, particularly stemming from heavy machinery and ongoing operations. Ensuring adequate shore power capacity despite volatile cold ironing demand remains a concern for reliable and efficient port operations. It needs enough power capacity to deliver the required energy and insufficient port power will require extra transmission infrastructure costs.

1.3.2. Seaport microgrids

The seaport microgrid concept is getting close attention from the maritime industry at present. Formerly, maritime power systems heavily relied on the national grid and fossil fuels. The ports have not been focused on energy concerns, and the interaction between a seaport and ships has primarily revolved around logistical operations, such as cargo handling, where onboard auxiliary generators remain active throughout the entire service duration.

The growing focus on electrification and green maritime aim has prompted a shift towards reliable and clean energy solutions. As the port infrastructure expands and operations become more diverse, the energy demand in ports is on the rise. Relying solely on grid power is no longer sufficient and might not be also always economical, leading to power shortages and environmental pollution from fossil fuel combustion. To address these challenges, ports are exploring clean energy resources and energy storage systems, with some even establishing their renewable energy power plants. For instance, Hamburg port draws 24.5 MW of power from over 20 wind turbines, utilizing solar panels on warehouse rooftops to generate 500 MWh of electricity annually [33].

A microgrid is a localized energy network that effectively integrates distributed energy resources (DERs) such as renewable energy sources, energy storage devices, and loads. Microgrids can operate either independently in island mode (disconnected from the main utility grid) or in a grid-connected mode, utilizing intelligent monitoring and control systems to effectively manage energy flow. Recently, the

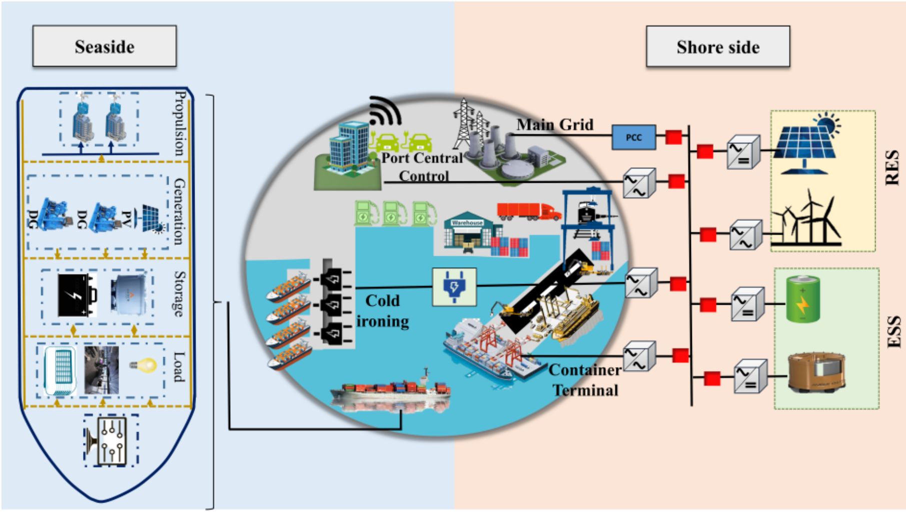


Fig. 1.9. The emerging microgrid concept in both shore and seaside.

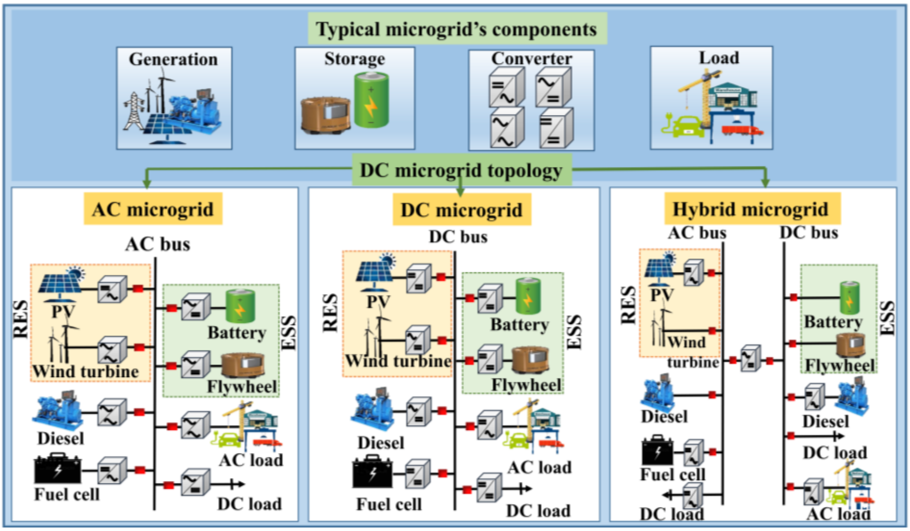


Fig. 1.10. Seaport microgrid topology.

seaport microgrid concept has been introduced to integrate clean energy solutions both on the shipside (shipboard microgrid) and shoreside (seaport microgrid). Fig. 1.9 shows the integration of microgrid concepts on the shoreside and seaside. Microgrids aim to improve energy resilience by minimizing dependence on the main grid, offering backup power during outages, and optimizing energy utilization in comparison to sole reliance on the grid. Seaport microgrid frameworks commonly fall into three categories: (1) AC microgrids, (2) DC microgrids, and (3) hybrid AC/DC microgrids, each with distinct topologies and network structures, as depicted in Fig. 1.10.

Despite the widespread development and maturity of terrestrial microgrids (microgrids on land) worldwide, their implementation in harbor areas has remained limited. The challenges in port environments, such as the diversity of loads and specific operational requirements, contribute to the slower adoption of microgrid technology in seaports. Seaport microgrids are tailored for maritime environments, specifically addressing the energy requirements of seaports, including ships, port equipment, and other maritime operations. Seaport microgrids are more vulnerable to load profiling uncertainties because of dynamic maritime operations. This dynamic behavior is triggered by a diverse array of loads and logistics services, from coordination with ship power to powering heavy port equipment like cranes, lighting systems, refrigerated storage systems, and port buildings. Besides, seaport microgrids are required to handle fast load fluctuations from frequent ship arrivals and departures. The port is also restricted by strict regulations that are subject to periodic revisions from time to time, thus operational management of seaport microgrids needs regular improvement [15]. Additionally, seaport microgrids must address the harsh marine environment with specialized waterproofing.

In summary, while both terrestrial and seaport microgrids share common fundamental principles, the specific applications and additional complexity of seaport microgrids call for specialized energy and operation management strategies.

1.3.2.1 The role of seaport microgrids in the integration of cold ironing systems

The great benefit of cold ironing compared to other competitive ship emission solutions of low sulfur fuel oil and scrubber technology is its capability to collaborate with the microgrid network. Fig. 1.11 depicts the concept of cold ironing and microgrid at the port site, where the collaborative between seaport microgrid and cold ironing play a crucial role in addressing environment control, energy accessibility, and economic challenges.

Environment control

Cold ironing primarily eliminates emissions from ships but not from the shoreside. Cold ironing's strong reliance on the main grid, predominantly powered by fossil fuels, poses a drawback. A seaport microgrid is a solution to realize both ship and shore emission control. Achieving substantial emissions reduction on the shoreside requires transitioning to cleaner energy sources, emphasizing the microgrids' potential as an alternative resource. The extent of emission reduction, however, is contingent on the proportion of clean energy integrated into the system. Further research investigation on microgrid and cold ironing incorporation may give the maritime sector new viewpoints on maximal-scale port decarbonization and enable them to take better decisions to benefit from both technologies.

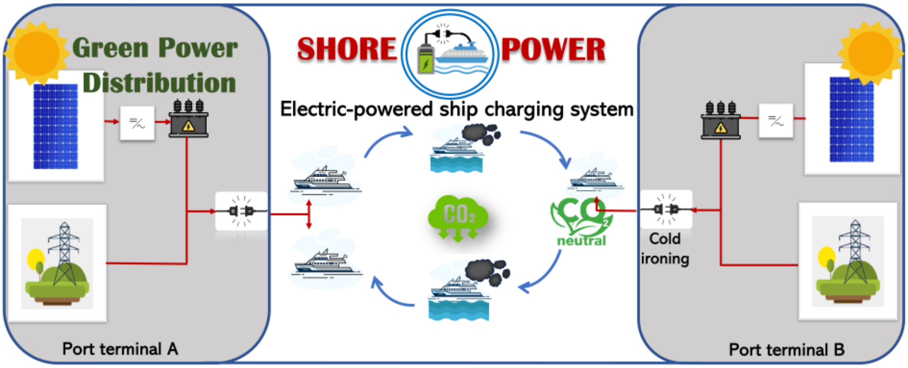


Fig. 1.11. Empowering sustainable maritime practices: The integration of seaport microgrids for cold ironing solutions

Energy accessibility

The port is a complex system with existing huge loads from various operations and logistics. The continuous high-power consumption of cold ironing facilities, particularly during periods of peak consumption driven by heavy ship traffic and concurrent energy needs from multiple large vessels, can potentially trigger power outages and operational disruption. Conventional ports struggle with fluctuating demand, particularly remote ports far from the national grid. Dealing with such fluctuations would require significant investments in extension grid infrastructure, including substations, transmission lines, and transformers, making it an unfeasible solution to the port with budget constraints. However, local ports' power generation from microgrids, capable of operating both grid-connected and independently during utility failures offer energy flexibility and ensure electricity security for seamless port operations.

Economical challenges

Shipowners favor the electricity generated by onboard auxiliary generators due to its cost advantage, benefiting from tax exemptions [34]. On the contrary, the electricity supplied by cold-ironing facilities sourced from the national grid incurs taxes, creating a great hesitation to shipping lines. A well-designed seaport microgrid, controlled by an efficient energy management system can overcome this economic barrier, profiting both port operator and ship owner. The variety of resources in a microgrid allows ports to dispatch energy cost-effectively while shipowners also gain tax reductions resulting from reduced purchasing energy grid. Although the implementation of seaport microgrids necessitates an additional capital investment for port operators, the substantial presence of ports with existing microgrids features the viability of a synergistic approach with cold ironing without imposing added costs. For instance, the Port of San Diego successfully implemented a microgrid solution, powering its

Tenth Avenue Marine Terminal with cold ironing facilities using 700 kW of solar panels and 700 kW of energy storage systems [18].

Despite the apparent advantages, the coordination of cold ironing and seaport microgrid encounter a complex challenge, encompassing energy flow and integrated logistical issues associated with handling activities. Addressing this challenge necessitates the modeling of an operational optimization and energy management framework to bridge technological gaps in the conventional port operational paradigm with advanced solutions.

1.4. Port management system

Port management systems (PMS) are advanced solutions designed to optimize and automate operations at busy seaports. They deliver a centralized platform to monitor, coordinate, and control various port processes, assets, and activities as illustrated in Fig. 1.12. Core functionalities of PMSs include controlling energy flow, routing cargo through terminals, managing equipment and human resources, coordinating ships and shore vehicles, upholding security protocols, integrating with logistics networks, and analyzing performance data.

These operational management capabilities are enabled by real-time sensors, Internet-of-Things devices, communication networks, databases, analytics, and process automation throughout the port. As ports grow in size and complexity, these smart systems are becoming essential to seamlessly organize port functionality. Their ability to optimize the use of port resources and infrastructure provides ports with significant competitive advantages.

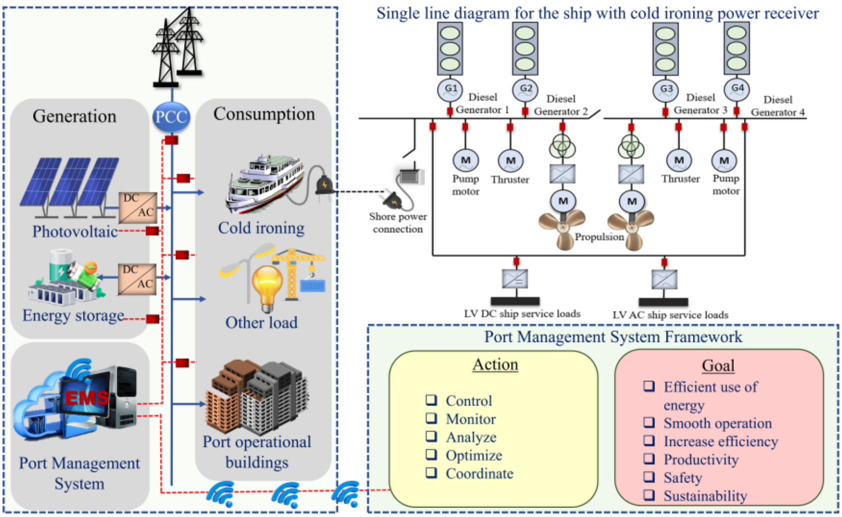


Fig. 1.12. Port management system.

1.4.1. Ports control, operation, and energy management

To allow ports to adopt cold ironing while ensuring smooth operations, two key management aspects must be addressed 1) operational management and 2) energy management. Fig. 1.13 illustrates the scope of operational and energy management for a port terminal.

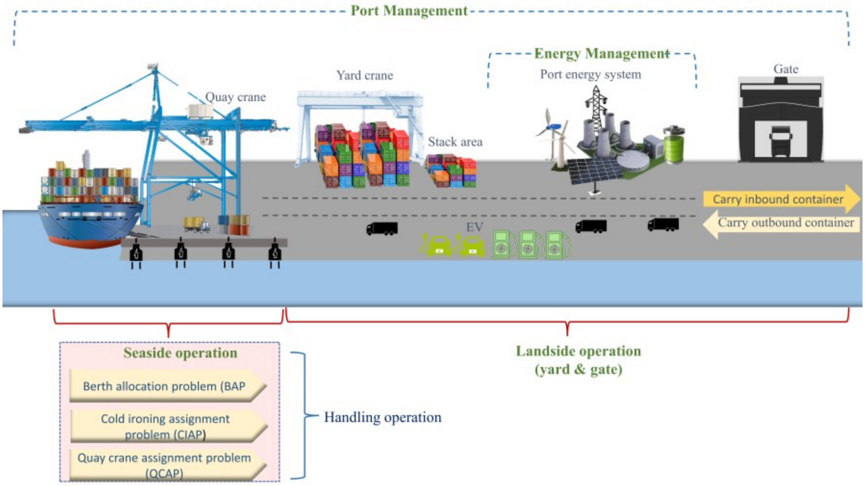


Fig.1.13. The scope of port management operations.

Cold ironing connection processes add constraints to existing port workflows. As they become new port resources, operational procedures need to be updated, to avoid poor handling performance. Monitoring and maintaining new cold ironing assets further increase operational responsibilities.

Additionally, cold ironing execution introduces new electrical loads that must be balanced with existing port energy demands. High power requirements from visiting ships may necessitate adopting a microgrid electrification solution for cost-effective and flexible demand management. It is important to attract ships to utilize cold ironing through competitive pricing and services. Apart from cost-benefit concerns, consideration of emission goals requires a multi-objective approach that can make a satisfactory tradeoff. Accordingly, proper handling of port workflows, asset coordination, and energy optimization is vital to assimilating cold ironing technology constructively. Focusing on operational and energy management will enable ports to integrate cold ironing while mitigating disruptions and maximizing sustainability and performance gains.

These operations and energy management at ports require strategic control measures. A hierarchical control structure enables coordination across diverse port assets, activities, and power resources. In a hierarchical architecture, control complexity is distributed among different levels - primary, secondary, and tertiary.

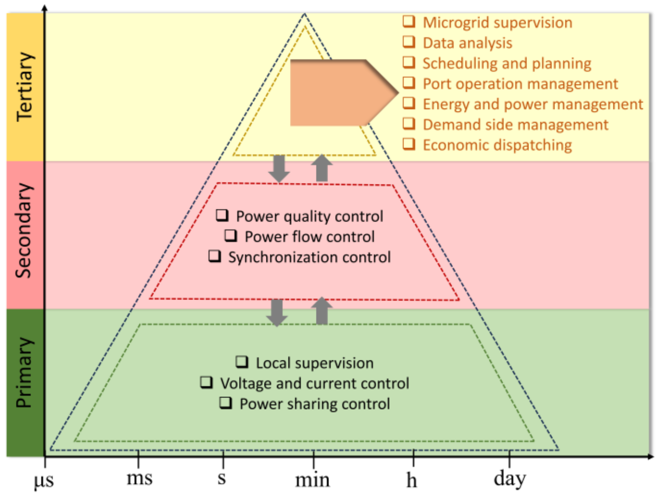


Fig. 1.14. The hierarchical control structure.

These levels share information, and the higher supervisory levels create setpoints for the lower levels. Each level is assigned specific control responsibilities that involve different control aspects, objectives, and timescales. Fig 1.14 visualizes the hierarchical control structure of a microgrid. The primary control layer focuses on controlling inverters, performing preliminary power sharings, and regulating voltage and current output. The secondary control layer oversees the coordination of the port's distributed energy resources such as between power generators, energy storage systems, and loads within the seaport microgrid. It maintains nominal bus voltage, frequency, and power quality based on setpoints from the upper control layers. This Ph.D. work particularly delves into the tertiary layer, which plays a crucial role in efficiently managing both operational activities and energy resources. The tertiary layer is the highest supervisory level in the control scheme to handle high-level port-wide energy optimization and operational decision-making. It organizes asset operations based on broader port objectives across interconnected port processes and resources.

1.4.2. Learning-based and optimization-based strategies for port management

Learning-based and optimization-based strategies are commonly applied as integral modules within operation management systems for multifaceted systems such as in maritime environments. Each approach has complementary strengths that, when combined appropriately, can enhance the performance and adaptability of these systems.

Learning modules

Cold ironing power consumption that is strongly related to ship transportation exhibits variability due to many external factors at ports. Interactions between these external elements and technology applications create challenges to uncovering the trend in electricity consumption. The integration of renewable energy resources to seaport microgrids with high intermittency in the output power further increases these challenges.

Learning-based approaches using artificial intelligence leverage statistical data to discern concealed patterns, relationships, and predictive insights solely from data. Gathering more data from a long-time horizon will increase the accuracy where future patterns can be predicted effectively. Common techniques include regression, classification, clustering, neural networks, and reinforcement learning [35].

As it learns directly from data, this method excels at handling nonlinearity that normally faced by the port sector with diverse operations. Various maritime applications demonstrate growing usage of learning-based modules for forecasting the terminal load [36], ship thruster power demand [37], real-time electricity price of shore power [38], electric crane power consumption [39], and seaport microgrid renewable power [40].

Despite their efficacy, the need for large historical data, time-consuming data processes, and training procedures exert significant pressure on computational resources, potentially limiting real-time deployment. Moreover, these approaches heavily rely on high-quality training data and are prone to bias from imperfect data.

Optimization modules

While learning modules learn from historical data, optimization modules use mathematical models to find optimal solutions that maximize or minimize an objective function subject to several constraints. It is required to develop a model with the involvement of decision variables, objective function, and constraints as shown in Fig. 1.15. Optimization-based methods be applied both in real-time and offline problems to generate optimal solutions.

In the maritime sector, the optimization module plays a pivotal role in enhancing operational efficiency and energy management. Proven by optimizing the port operation in [41] managed to increase the port productivity by 20%. The authors in [42] ensure ship operation safety with port waterway system optimization. The study by [43] proposes an optimization strategy to optimally supply energy needs at the port and quantifies the economic cost of the peak load burden.

This module is designed to systematically analyze and improve various aspects of port operations, considering factors such as ship traffic, cargo handling, and energy consumption. It considers operational parameters, asset availability, energy prices, equipment constraints, and environmental goals, among others. The module employs techniques like linear programming, mixed-integer programming, and other programming methods to process this interconnected multi-source data. It then creates

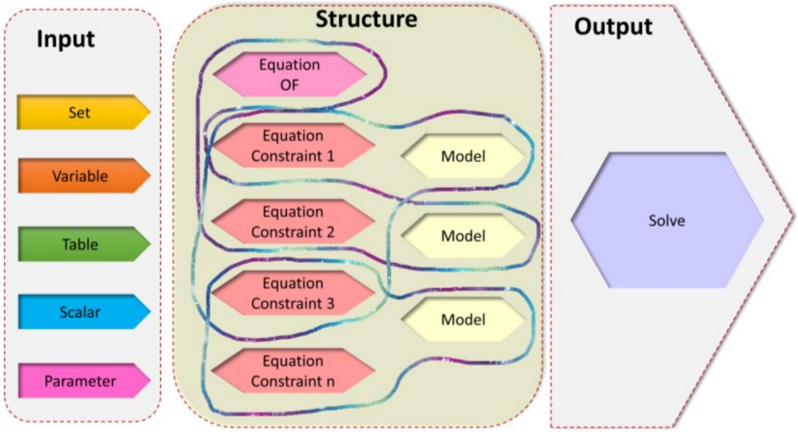


Fig. 1.15. Composition of the optimization model.

an optimization model to identify ideal solutions that minimize costs and emissions while satisfying all requirements. These plans guide decisions on aspects like berth allocation, yard crane scheduling, charging of electric vehicles, load balancing, microgrid control, and utilization of assets like storage batteries. However, the growth in computational complexity for large problems is a disadvantage.

1.5. Research questions

Considering several issues found in the port operation while integrated with the shore power of cold ironing, the following are the scientific research questions:

1) How should the uncertain behavior of power demand from cold ironing be managed to maximize the operational efficiency of ports and minimize load interruption?
2) How can port operation and cold ironing systems be coordinated to improve the satisfaction levels of operators at both ship and shore sides?
3) How can microgrid energy management techniques enhance emission reduction at seaports with cold-ironing facilities and maximize their economic profit while guaranteeing service continuity?

1.6. Thesis objectives

In this Ph.D. project, an energy management and operation optimization framework are developed for the seaside port operation with optimal coordination between the shore power system of cold ironing and the seaport microgrid, to minimize the emission at ports. In this sense, the following sub-objectives will be considered:

1) Development of novel forecasting techniques to forecast ships' berthing duration.
2) Modeling the optimization framework for optimal scheduling of seaside port operations that integrates a cold ironing system by considering the operating constraints and available port resources.
3) Development of a novel coordinated energy management system of seaport microgrid integrated with cold ironing. The problem formulation will be set to meet seaport operation and energy requirements, as well as the need to minimize environmental impact while maximizing economic profit.

1.7. Thesis outline

This thesis is written as a compilation of journal articles and conference papers, organized into five chapters as follows:

Chapter 1: Addresses the state-of-the-art of port electrification, highlighting the current challenges, environmental issues of the maritime industry as well as emerging solutions involving seaport microgrids and cold ironing technology. The research motivations and objectives are presented, emphasizing the need to coordinate electrification with port operations and energy management strategy.

Chapter 2: Presents a data-driven forecasting technique for predicting the berthing duration of ships at ports to estimate the power demand of the cold ironing system.

Chapter 3: Develop the optimization model for the seaside operations to enhance the port performance while integrating cold ironing technology into the operation.

Chapter 4: Proposes a novel energy management system that coordinates the operation of seaport microgrids and cold ironing systems at container ports with consideration of various operational constraints.

Chapter 5: Presents the overall conclusion of the thesis, the thesis contributions, and future directions identified by this study.

Chapter 2. Forecasting of ship berthing durations at ports with cold ironing

2.1. Introduction

The behavior of cold ironing power consumption is strongly related to the ship's transportation. Accordingly, the stay duration of the ships at the port while berthing is an important measure as a lengthy berthing period of the ship will consume more power from cold ironing and potentially cause congestion in port traffic resulting in extended waiting periods for other ships to start berthing. Besides, it is an important parameter to estimate the amount of pollution that can be avoided with the cold ironing implementation. Being capable of accurately assessing a ship's berthing duration at the port can help the port operator in optimally arranging the berth allocation and performing optimal energy scheduling. Nevertheless, the identification of various factors that influence the dynamic pattern of ships berthing in the port is a great challenge to formulating a good load forecasting method. In addition, the involvement of many input parameters as shown in Fig. 2.1 with a large dataset requires the deployment of advanced forecasting practices. Accordingly, various data-driven forecasting techniques such as artificial neural networks, multiple linear regression, random forest, decision trees, and extreme gradient boosting are investigated in this chapter. The highly accurate forecast output of berthing duration will contribute to the precise prediction of two significant parameters for port operators, namely cold ironing power consumption, and the ships' departure time. Each of them is vital to be utilized in the energy management system (EMS) and the berth allocation problem (BAP).

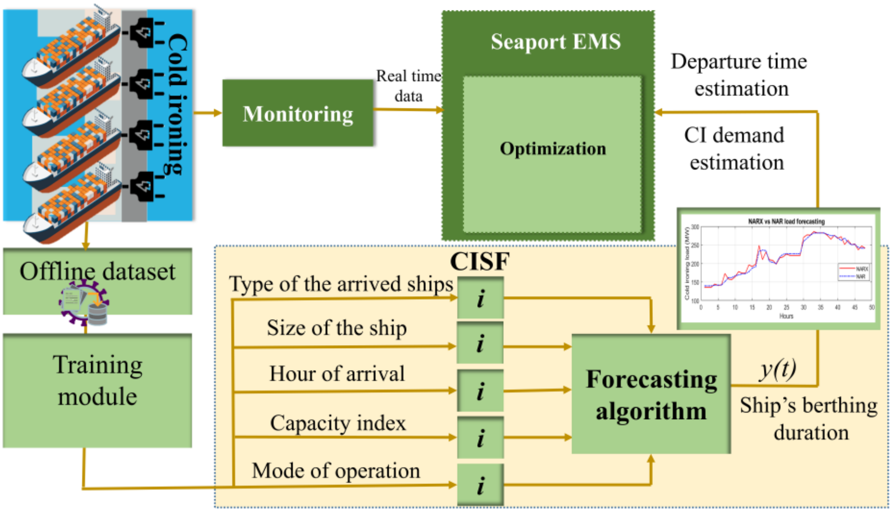


Fig. 2.1. Forecasting inputs data and output.

2.2. Methodology

2.2.1. Background of the study

The seaport activity dataset for this study is collected from Port of Aalborg's ship tracking system [44]. Fig. 2.2 presents the ship arrival trend at the Port of Aalborg for a year, illustrating various types of visiting ships at the port.

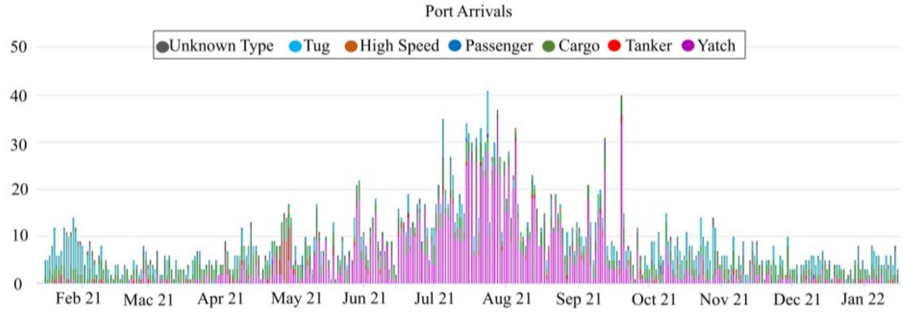


Fig. 2.2. The call of ships at the Port of Aalborg from February 2021 until Jan 2022.

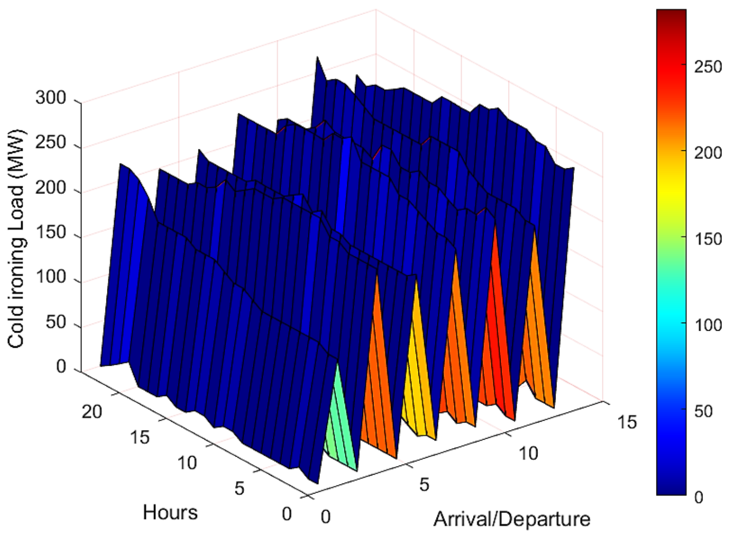


Fig. 2.3. Fluctuation of cold ironing hourly power consumption with the ships' arrival/departure frequency.

In this study, only cargo and tanker types of ships are considered as they feature long berthing duration, huge, and have frequent port visits. Other than the ship's type, a nonlinear relationship is found between the frequency of ships' arrival and departure every hour, ship power demand, and berthing period as shown in Fig. 2.3. All these factors influence the power usage of the cold ironing, which leads to a dynamic load behavior. Thus, to guarantee that the forecasting method can replicate the intended output with the lowest possible error, the influential factors must be considered.

The forecasting algorithm is trained with one-month ship data (28 days) where $t \in 1,2,3 \ldots 672\ (h)$ to forecast the stay duration for the future incoming ships of the same type. Realizing that ship berthing durations can vary from a few hours to several days, a 672-hour timeframe works best for observation of ships' berthing patterns. Table 2.1 shows the statistical analysis used in the training module of all the input parameters which are arrival time, ship type, operation mode, and ship index capacity. This analysis is performed in the data cleaning process to avoid duplicated data, outliers, invalid values, and data shortages that might disrupt the training process. In this case, the desired forecasting output is the ship berthing duration. All forecasting models were run with Spider (Phyton 3.9) and the Matlab interface. Fig. 2.4 outlines the flow chart of the proposed forecasting technique.

Table 2.1. Statistical dataset used for training of the forecasting method.

	Arrival time (a.m/p.m)	Cargo arrival	Tanker arrival	Cargo size (m^2)	Tanker size (m^2)	Cargo mode of operation	Tanker mode of operation	Cargo index capacity	Tanker index capacity	Cargo berthing (h)	Tanker berthing (h)
Count	672	672	672	672	672	672	672	672	672	672	672
Mean	11.5	0.079	0.03	118.26	39.63	0.077	0.013	8.444	5.01	2.8476	0.311
Std	6.93	0.27	0.17	498.06	544.63	0.27	0.12	59.41	65.72	15.84	2.58
Min	0	0	0	0	0	0	0	0	0	0	0
Max	23	1	1	5510	13152	1	1	1056	1644	264	37

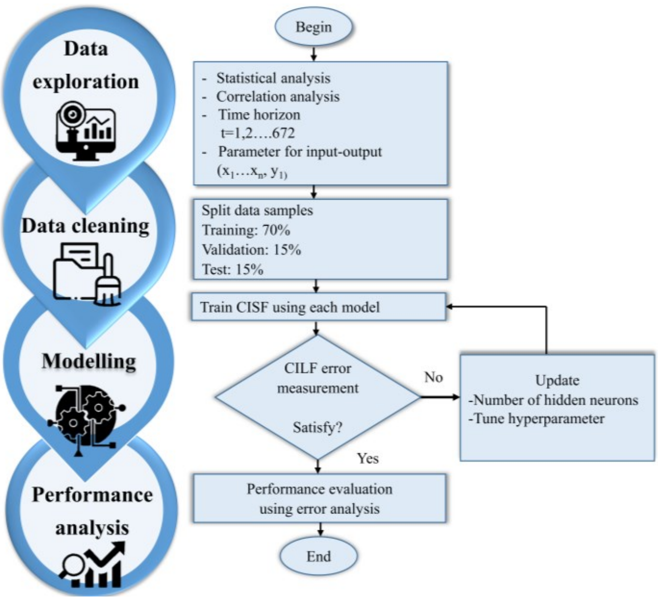


Fig. 2.4. Training module flow chart.

2.2.2. Correlation analysis

The purpose of the correlation analysis is to discover the strong relationship between any two selected variables. The Pearson correlation mapping between selected data was used and the result is shown in Fig. 2.5. It shows that when the coefficient approaches one, it implies a true correlation occurs between variables. For instance, cargo arrival and cargo mode of operation are strongly correlated (0.99), while cargo berthing hour and tanker mode of operation are not related as the correlation value is approaching 0.

Fig. 2.6. gives a more detailed relationship analysis through the pair plot method for all the variables including time of arrival, berthing duration, index capacity, ship's size, ship's type, and mode of operation. The pair plot shows that a bigger index capacity and a later arrival time increase the berthing duration. Besides, a linear relationship is created between the ship's size and the berthing hour.

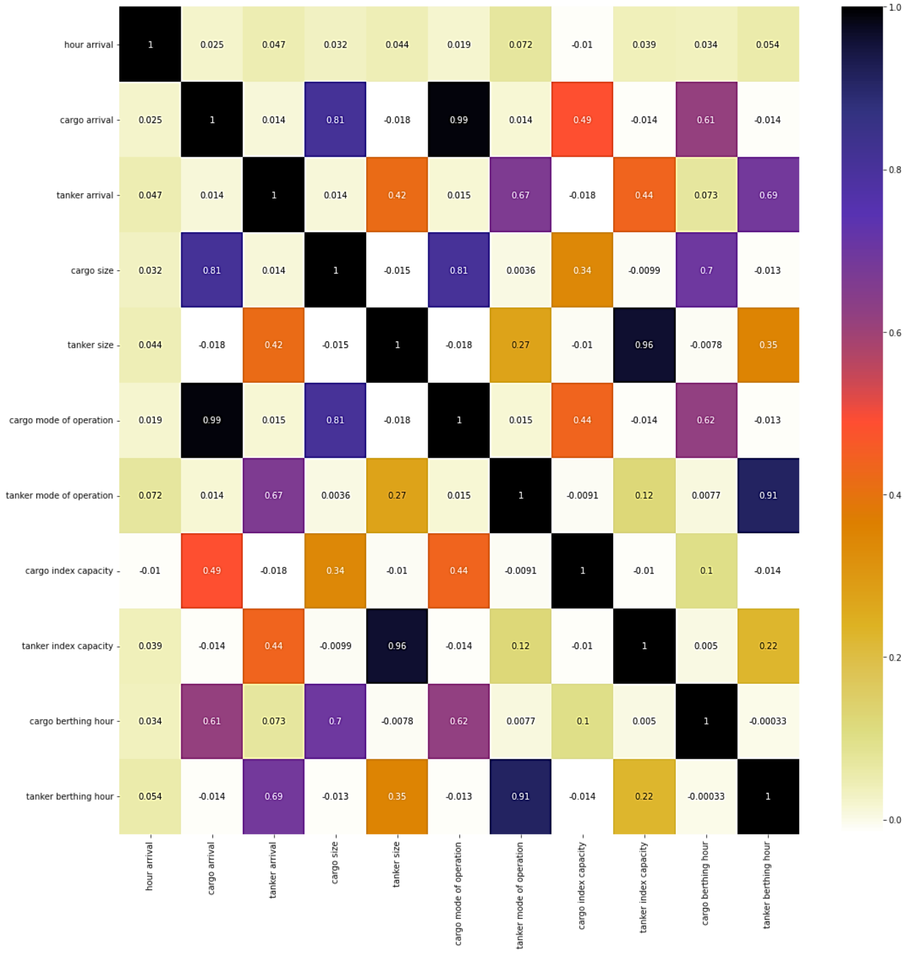


Fig. 2.5. Pearson correlation matrix of the ship berthing forecasting.

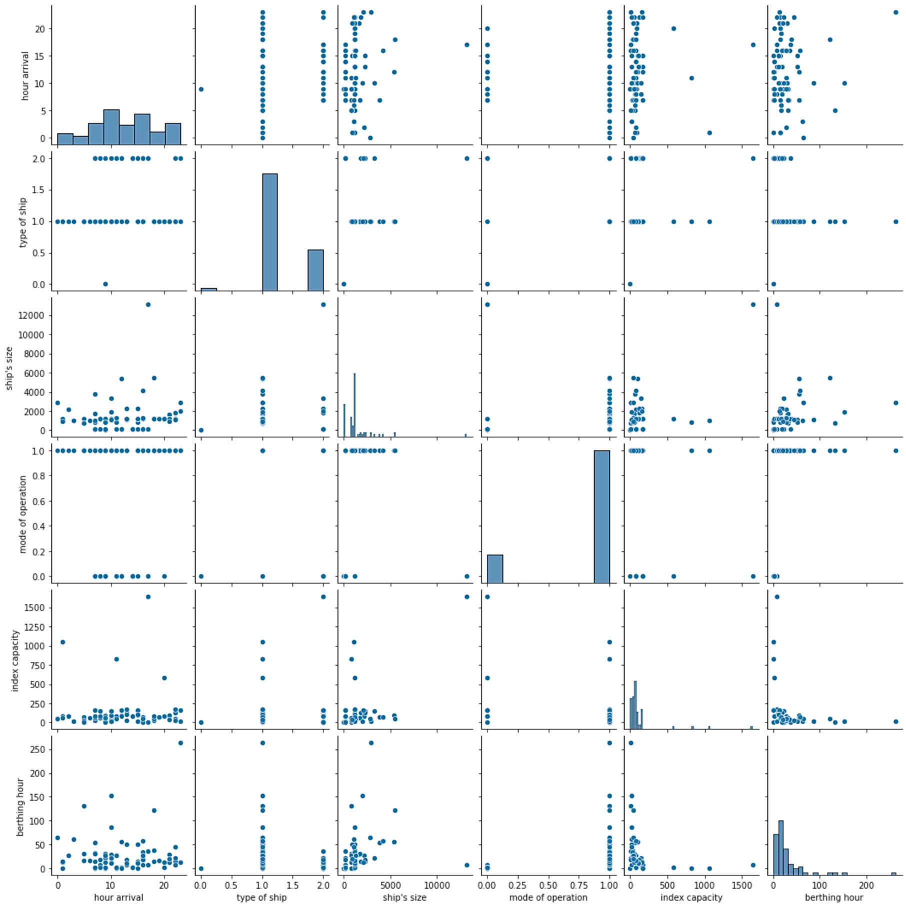


Fig. 2.6. The pair plot for the ship dataset.

2.2.3. Data-driven forecasting model for ship stay duration prediction

Artificial Neural Network (ANN)

The proposed ANN networks are constructed with 10 hidden layers and 9 inputs as shown in Fig. 2.7. The algorithm used for training the network is Levenberg-Marquardt (LM) backpropagation. There are n sample inputs represented $x = [x_1, x_2, \ldots, x_n]$ that are allocated to the weights w_1 to w_n and the biases vector of b. The w_i and b's weight elements are scalar parameters that can be modified. These inputs are routed to the m hidden layers. As a result, the net output function is determined as follows:

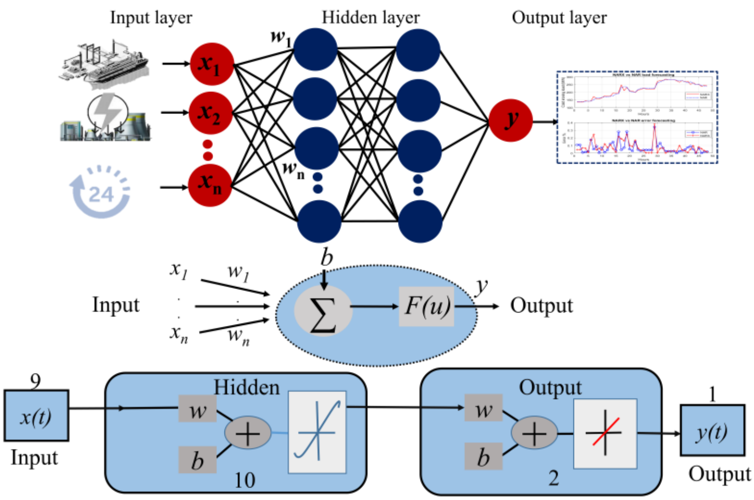


Fig. 2.7. Proposed ANN model.

$$y = \sum_{i=1}^{n} x_i w_i + b \tag{2.1}$$

Multiple linear regression (MLR)

The MLR is calculated using equation (2.2), where y is a dependent variable, $x_1, x_2, \dots, x_n$ are the independent variables, and $a_0, a_1, \dots, a_n$ are the coefficients.

$$y = a_0 + a_1 x_1 + \cdots + a_n x_n \tag{2.2}$$

Decision Tree

Decision Tree is a decision-making solution with a flowchart-like tree structure that works with both continuous and categorical inputs shown in Fig. 2.8.

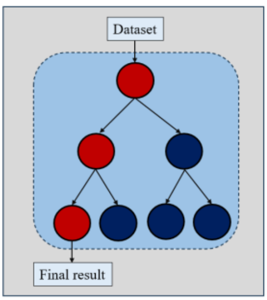


Fig. 2.8. Decision tree concept.

In most circumstances, mean square error is employed to create the dividing sub-node. The branches may reflect the conditions (decision nodes) or the result (end nodes).

Random forest

Given the information in the dataset, the random forest generates many subgroup decision trees. After that, a new tree is created for each subgroup, and the process is continued until the most accurate prediction has been determined [35]. The forecasts of each tree are gathered, and the total value is averaged. Fig. 2.9 shows the random forest structure.

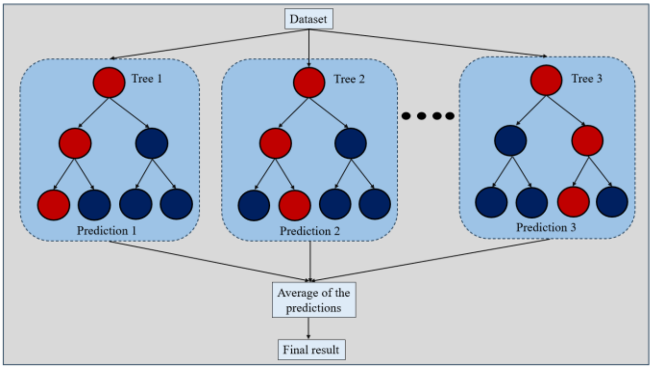


Fig. 2.9. Random forest structure.

Extreme Gradient Boosting

The forecasting algorithm called extreme gradient boosting (XG Boost) can be employed to tackle regression predictive modeling challenges. It follows the principle of staging the prediction, having the subsequent stage aimed at minimizing the error of the previous stage. The key goal is to obtain the required result with minimum error as possible over the whole data. Equation (2.3) [45] is used to derive the XG Boost model.

$$\hat{y}_i = \sum_{k=1}^{K} f_k(x_i), f_k \in F \tag{2.3}$$

where k is the number of decision-tree, $f_k(x_i)$ denotes the function of input in the kth decision-tree, and $\hat{y}_i$ is the predicted value.

2.2.4. Performance indicators

The performance and accuracy of the forecasting algorithm are evaluated by using key performance indicators (KPI). Mean absolute error (MAE), Root Mean Square

Error (RMSE), and coefficient of determination (R2) are the most widely utilized KPIs [46], [47]. The following are the KPI formulations:

$$\mathrm{MAE} = \frac{1}{N}\sum_{n=1}^{N}\left|y_n - y'_n\right| \tag{2.4}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(y_n - y'_n)^2} \tag{2.5}$$

$$R^2 = 1 - \frac{\sum_{n=1}^{N}(y_n - y'_n)^2}{\sum_{n=1}^{N}(y_n - k)^2} \tag{2.6}$$

where n is the number of data samples, N is the total number of data points, y represents the actual desired value, y' is the predicted value, and k denotes the mean of the actual value.

2.3. Simulation results and discussion

The main objective of the proposed training module is to forecast the target value as close to the actual output as possible. Fig. 2.10 compares the actual values as opposed to the generated forecasting values from all proposed data-driven algorithms, namely ANN, MLR, random forest, XG Boost, and decision tree. It can be observed that ANN and decision tree successfully reproduce the actual berthing duration from a large part of the ships' sample data with negligible error. In contrast, MLR prediction with a large error shows the poorest performance in this case. In the rest of the algorithms, an average performance can be observed.

Several forecasting error indicators such as RMSE, MAE, and R2 are analyzed to assess the accuracy of the candidate methods. The results are summarized in Table 2.2. It shows that ANN outperforms other algorithms with the lowest RMSE and MAE error values of 3.1343 and 0.2548, respectively. Conversely, the MLR performs poorly as indicated by the highest error validation across all metrics: RMSE of 55.43, MAE of 2.0825, and R2 of 11.51%. This outcome can be attributed to the characteristic nature of MLR, which models relationships between continuous variables. However, the various involvements of the data input in this study, encompassing a combination of continuous, binary, and categorical variables increase the complexity of the input-output prediction. Additionally, a nonlinear relationship has been identified between the parameters of input and output, as depicted in Fig. 2.3. Consequently, a dynamic pattern of berthing duration for each visiting ship is observed. The ANN framework enables for deep learning from the input, thereby yielding higher prediction accuracy, particularly in scenarios influenced by external uncertainties and disturbances. Due to these inherent strengths, ANN surpasses other algorithms and emerges as the preferred model for forecasting ship's berthing duration.

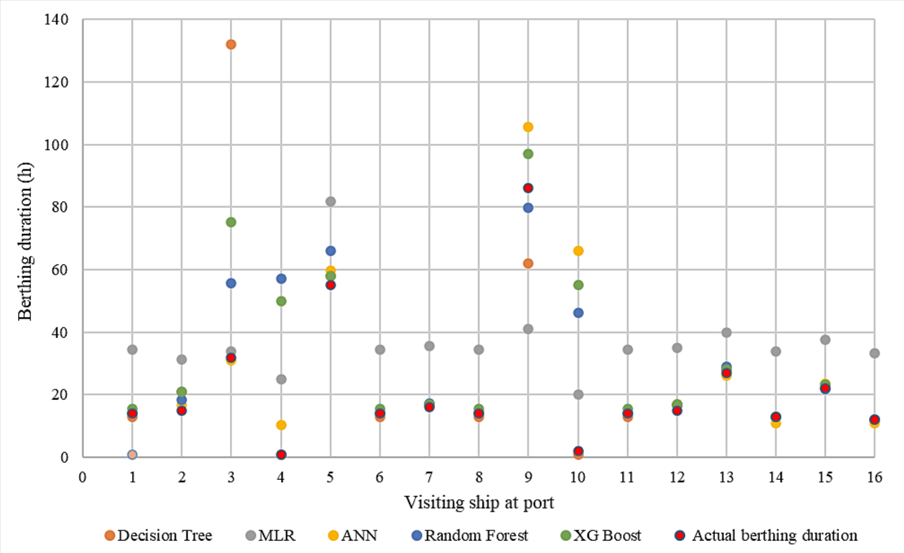
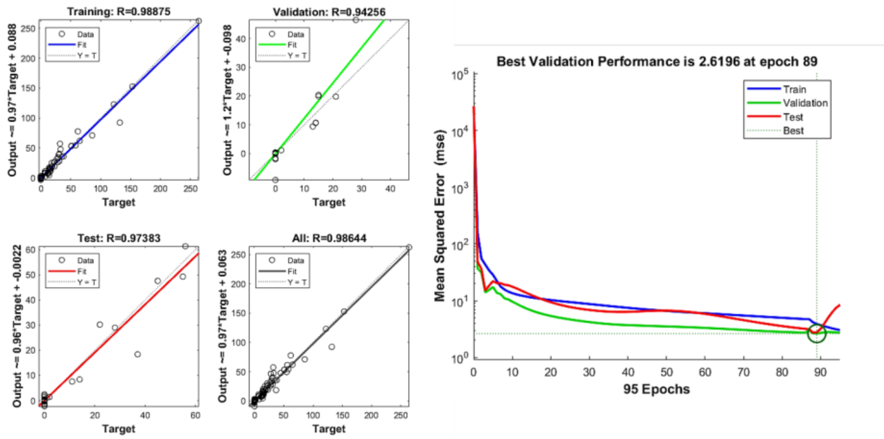


Fig. 2.10. Comparison of the actual and forecasted value for all candidate methods.

Table 2.2. Evaluating KPIs for the candidate methods.

Model	Category of error		
	RMSE	R^2 (%)	MAE
ANN	3.1343	98.64	0.2548
MLR	55.434	11.51	2.0825
Random Forest	5.5473	91.14	0.3346
XG Boost	9.2918	85.16	0.3661
Decision tree	3.9369	93.71	0.2972

The final assessment of the comprehensive regression performance is required since the ANN has been chosen as one of the best approaches. The result in Fig. 2.11 shows that the average performance of the ANN is 0.98875, 0.94256, and 0.97383 in training, validation, and testing, respectively. The average value for the overall performance is 98.644%, suggesting that the model is proficient in forecasting. Thus, ANN is selected to forecast ship stay duration using a new dataset for two different types of ships, namely cargo and tanker. The result shown in Fig. 2.12 demonstrates that the majority of forecasted ships' calling at the port closely resembles the actual value of berthing duration. It implies that there exists a substantial correlation between the selected input variables and the berthing duration patterns of ships. In terms of forecasting error, the cargo type of ship exhibits the highest error rate, reaching 40%.



(a) Overall performance (b) MSE validation performance

Fig. 2.11. ANN forecasting performance.

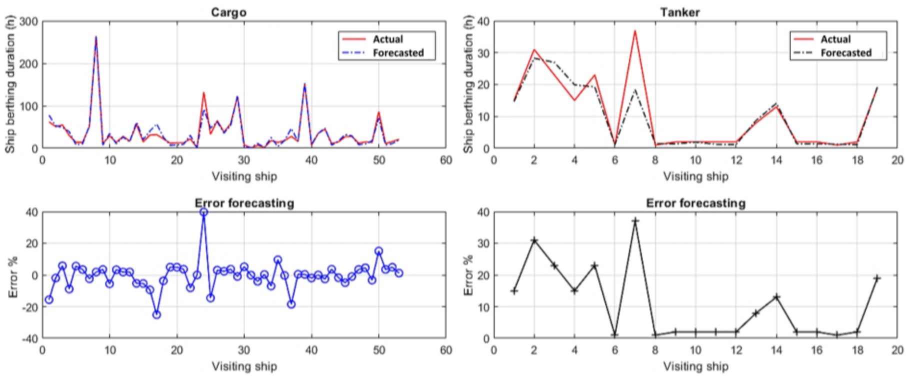


Fig. 2.12. Forecasting results for different types of ships using ANN.

Similarly, the tanker type of ship forecasts shows the highest error rate of 38%. These discrepancies could likely be attributed to the presence of null variables, which impede the accuracy of the target output. Furthermore, the forecasting ability of data-driven approach is heavily reliant on the quality of the training data. Therefore, in regions where there are sharp changes in parameter values, a notable error deviation may occur.

The selection of input variables for this forecasting study may influence the berthing duration from a different perspective. Each type of ship possesses its unique characteristics, functions, and requirements to fulfill. The presence of unpredictable variables gives a significant challenge in achieving precise output. For instance, the ship that has been scheduled to arrive at the port can experience sudden changes. While the port has access to the ship's arrival information in advance through an automatic identification system (AIS), unforeseen circumstances such as weather conditions, technical issues, and special requests for expedited arrival can result in sudden alterations to the tentative schedule. These uncontrollable events may lead to delays or early arrivals at the port, deviating from the planned arrival time. Additionally, the hour of arrival greatly impacts the berthing period. Arriving during peak times may result in longer waiting times, whereas late-night arrivals can lead to extended handling operations due to limited manpower availability. Furthermore, the size of the ship is a crucial factor to consider. Larger ships can carry more goods, which in turn require more time for handling services. However, certain datasets imply that larger ships are capable of berthing within a shorter duration. This discrepancy might be attributed to the ship's mode of operation, including activities such as loading/unloading, transit, refueling, and port visits for maintenance, all of which entail different berthing hours. Despite the various input parameters involved, most of the ships calling at the port can closely replicate the actual berthing duration with minimal error. One of the novelties in this study is illustrating the strong correlation between the chosen input variables and the diverse patterns observed in the berthing duration for each visiting ship.

2.4. Summary of the contribution

(1) This study provides insights into the relationship between prospective inputs and how they could affect the ships' stay duration, which can help identification of the uncertain number of influencing factors that impact cold ironing power consumption.
(2) This input-output formulation has significance as it captures the important trends and builds an accurate forecasting model that can forecast the future berth duration of the ships and help plan essential actions ahead of time for the best possible performance.
(3) This study delivers a data-driven forecasting model for predicting ship berthing duration of ships to be supplied by cold ironing. Five data-driven forecasting techniques are executed including ANN, MLR, decision tree, random forest, and XGBoost. According to the comparative analysis, ANN is the best technique for the forecasting model with the lowest deviation error.

2.5. Conclusion

Forecasting of the berthing duration for ship holds significant importance to the port operators, particularly in management conduct. This thesis presented a data-driven approach that has been examined through simulation. Simulation results indicate that ANN, random forest, XG Boost, and decision tree exhibit commendable performance with respective RMSE values of 3.1343, 5.5473, 9.2918, and 3.9369. These findings suggest that ANN achieves the highest accuracy with the lowest error rate among all the forecasting models, thereby establishing an effective forecasting model for the ship berthing duration. Furthermore, the numerical results validated the applicability of the data-driven approach to berthing duration forecasting while showcasing the strong relationship between the selected input variables and output. However, it is important to note that the proposed method comes with a limitation: it necessitates a substantial amount of training data to ensure accurate training and close emulation of the real behavior. Acquiring such a large quantity of data may not always be practical. Therefore, it is crucial to develop new approaches that can be trained with limited data to address this challenge.

Chapter 3. Seaside operation optimization with cold ironing integration

3.1. Introduction

The ongoing demand for global trading corresponds with the continually growing activity of the international shipping business. Roughly speaking, 90% of imported and exported goods are transported through sea [48]. The number of cargo calls at ports continues to rise due to their cost-effectiveness and ability to carry large volumes of cargo. Hence, container terminals are tasked with handling a larger amount of cargo each year. In addition, bigger ships mooring at the terminal increases as their size increases in parallel with the workload of handling commodities. All led to expanding terminal operations, necessitating the allocation of additional port resources for handling processes. This places significant pressure on terminal management to ensure client satisfaction in a highly competitive maritime industry. The heavy shipping traffic not only triggers peak hours of load handling at ports but also has the potential to cause operation delays if not efficiently managed. Thus, operation management of container terminals is becoming a challenging task due to the rising scale of operations and imposed requirements resulting in complex integrated resource management problems.

Another challenge in container terminal planning is the emergence of adopting revolutionary technologies at ports, such as cold ironing systems. This interest stems from the need to address the environmental issues associated with ship activities. However, this transition toward electrification has further complicated the coordination of two existing operational problems in seaside terminals: berth allocation (BAP) and quay crane allocation (QCAP). Fig. 3.1 illustrates the container terminal issues that the port operators must tackle.

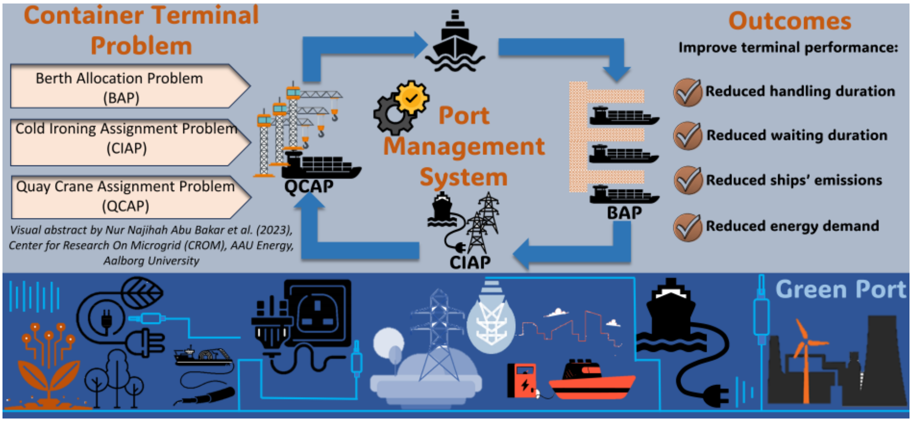


Fig. 3.1. Operation management issues at the seaside operation of a container terminal.

3.2. Integration of cold ironing into seaport operations

The integration of cold ironing into seaport operations introduces new problem, and the potential impact of this integration has yet to be quantitatively addressed. The incorporation of cold ironing into BAP and QCAP can lead to infeasible or poor berthing allocations. Currently, there is limited research on the combination of BAP and cold ironing, mainly due to the predominance of ships utilizing auxiliary engines instead of cold ironing. This choice is often driven by the high investment costs associated with cold ironing establishment at port and ship retrofitting.

Existing studies either formulate BAP individually or expand the scheduling complexity by combining it with QCAP. To address the terminal scheduling problem, mathematical programming optimization strategies have been widely adopted as a practical approach for planning and operational management. However, previous attempts to integrate cold ironing with BAP, as described in [6], have resulted in long waiting times for ships due to the limited cold ironing capacity at the port. These delays in operations not only incur contractual penalties but also diminish overall port service efficiency [49]. Given that the container terminal serves as a crucial business hub within the trading network, competition among container terminals is particularly fierce [50]. To gain a competitive advantage over neighboring ports, terminals need to enhance their cargo handling capabilities and minimize turnaround times. By doing so, they will attract more cargo ships and generate higher revenue. Therefore, port administrators must strive to improve service performance by reducing ship delay times.

Unfortunately, the upgrading of port facilities to enhance operational efficiency is hindered by the requirement of substantial investment costs. Research conducted in [18] indicates that upgrading the power capacity for cold ironing at each berth can reduce total handling time, but it entails expensive installation costs. Highlighting this challenge, strategic approaches are necessary to uphold service quality while keeping costs reasonable. A practical approach to mitigate additional costs for the port operator involves utilizing existing port resources, such as berth and quay cranes. The efficacy of this strategy is supported by the findings of [51], which emphasize that optimal utilization of existing port resources can enhance terminal work efficiency without the need for significant infrastructure investments. However, this aspect has not been extensively investigated by the existing studies. This knowledge gap serves as the motivation for this study, which aims to develop an integrated framework of seaside operation management with the coordination of BAP, QCAP, and cold ironing to improve terminal service time.

Accordingly, this chapter proposes an integrated optimization framework to cooperatively address the scheduling and assignment problems of BAP, QCAP, and cold ironing (CIAP) in seaside operations of container terminal. The optimization objective is to minimize the duration of ship stay at port including waiting time and handling time by optimizing the utilization of available port resources, thereby eliminating the need for additional investment costs associated with upgraded facilities.

3.3. Seaside operation at container terminals

The handling operations at the container terminal are classified into two divisions: landside and seaside operations, as depicted in Fig. 3.2. Due to the diverse data and logistic resource requirements, it is not feasible to address decision problems for the entire set of operations simultaneously [52]. Hence, the problem associated with each handling stage is examined independently [53].

The landside zone serves as the intermediary area connecting the port with the transportation and distribution of goods to and from external owners who are not located within the port [14]. This zone consists of two distinct functional areas: yard operation and gate operation [15]. It encompasses the utilization of machinery equipment and land transportation such as trucks and trains for goods transfer. On the other hand, the seaside zone primarily focuses on ship transportation, involving the allocation of arriving ships to appropriate berths and assigning multiple quay cranes for cargo loading and unloading purposes. The implementation of cold ironing and its significance are key aspects of the seaside operation, thus confining the scope of this study to the seaside operation of container terminals.

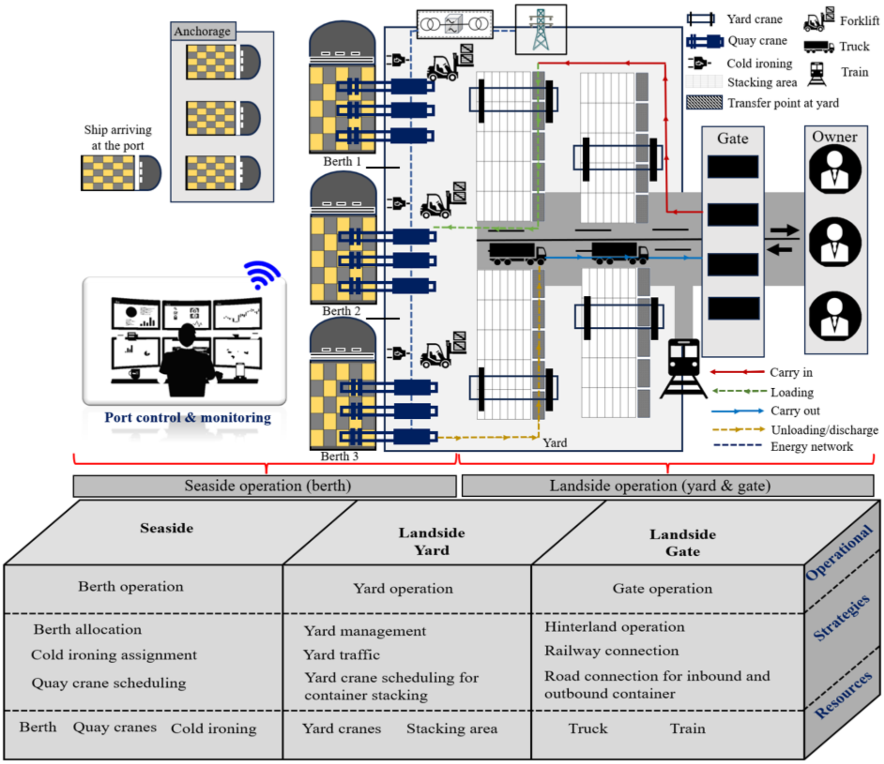


Fig. 3.2. Different zones of a container terminal and their operations.

3.4. Quay crane scheduling strategy

In the pursuit of delivering superior quality service, the feasibility of upgrading infrastructure and devices may be constrained by certain limitations. One such limitation involves the construction of a new berth space, which necessitates an available and unused area at the port. Similarly, enhancing the cold ironing capacity to a substantial level for each berth requires a significant investment. Nevertheless, according to the authors of [54], adept planning in the scheduling of quay cranes through the implementation of the QCAP right strategy can effectively minimize container terminal service durations and greatly enhance customer satisfaction.

There are two common strategies of QCAP, namely time-variant QCAP and time-invariant QCAP. Fig. 3.3 illustrates the structure of both schemes. In the time-variant QCAP strategy, the number of quay cranes assigned to serve a ship may vary during the handling period. Conversely, in the time-invariant policy, the quay cranes allocated to a ship must remain dedicated to that ship until the handling is completed. The time-variant strategy allows for optimal crane utilization by reassigning cranes currently in use on one ship to other arriving ships, thereby accelerating cargo handling [55]. Nevertheless, there has been a disagreement regarding the feasibility of implementing this strategy in practice. The free movement concept associated with this strategy results in significant crane movements and increased operational time losses, rendering it impractical to execute. Furthermore, it has been observed that applying this method to many ships over an extended planning horizon is unfeasible [56].

Incorporating a time-invariant strategy for quay crane scheduling minimizes the frequency of crane movements, as each crane is assigned to a ship and remains unchanged throughout the operational period [57]. The authors in [55] mention that time-invariant models have fewer variables, facilitating computational management. Due to these advantages, the time-invariant strategy is adopted in this study, considering the additional complexity introduced by the integration of cold ironing into the BAP and QCAP.

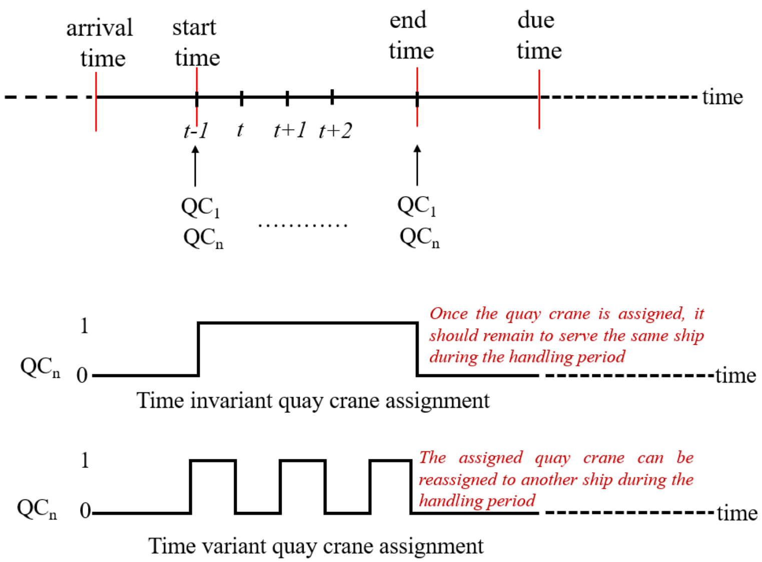


Fig. 3.3. The paradigm of time-variant and time-invariant for quay crane scheduling.

3.5. Seaside operation optimization model

3.5.1. Problem description

Despite the environmental mitigation advantages of cold ironing, its integration at the port harms traffic congestion, potentially leading to significant ship delays. Previous research conducted by the authors [6] confirms that the inclusion of cold ironing services in seaside operations results in extended waiting times for ship servicing,

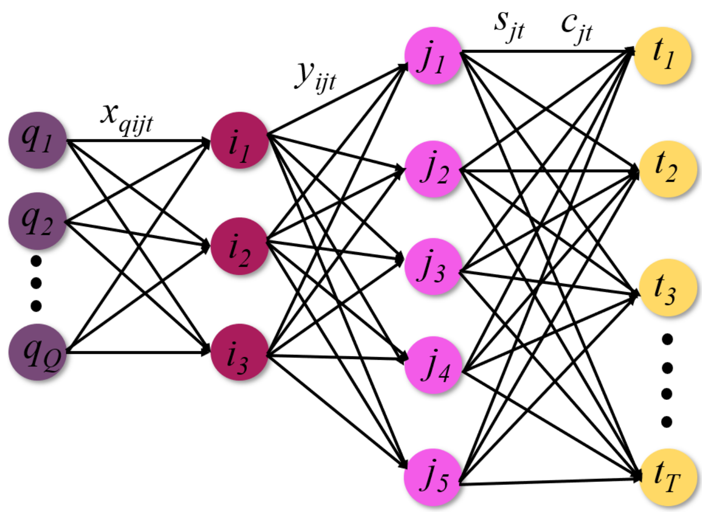


Fig. 3.4. Different scheduling problems at the seaside operation of a container terminal (q is the index of quay crane, i is the index of berth, j is the index for ship, t is the index of time, x_{qijt} is the decision variable for quay crane assignment, y_{ijt} is the decision variable for the berthing position, s_{jt} is the decision variable for ship position, c_{jt} is the decision variable of ship's connection status during handling)

primarily due to the limited capacity of cold ironing. Furthermore, integrating cold ironing adds complexity to conventional operation scheduling as it necessitates meticulous coordination between cold ironing scheduling and existing scheduling such as BAP and QCAP. Fig 3.4 displays the complex scheduling process associated with the seaside operation and the interdependencies between different scheduling tasks. The efficiency of the three scheduling tasks is greatly influenced by the management of port resources [32]. This issue serves as the motivation behind this study to identify a solution for enhancing port operation management performance while enabling ships to effectively utilize the shore-to-ship power system of cold ironing.

The staying time of the ships at the port becomes the vital parameter in this case study where it is measured by the sum of the waiting period and handling period. These two periods are the main variables in the entire process of the seaside operation. The waiting period is the interval that incoming ships from the waterway to the port must wait at the transfer point of the anchorage until the berthing time starts. Meanwhile, the period between the start time and end time of the operation during which the ships are attached to the cold ironing and the cargo is handled for loading and unloading with the help of quay crane machinery is referred to as handling time. Fig 3.5 shows the overall ship movement flow from their arrival until they depart from the container terminal.

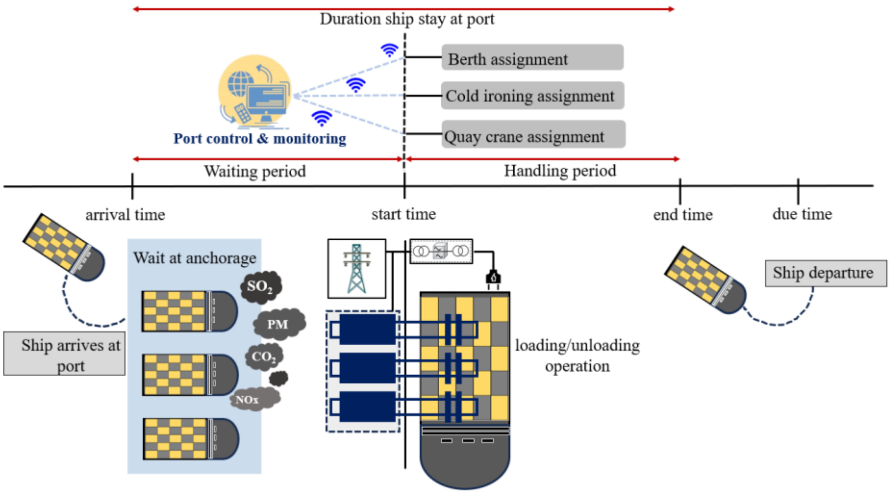
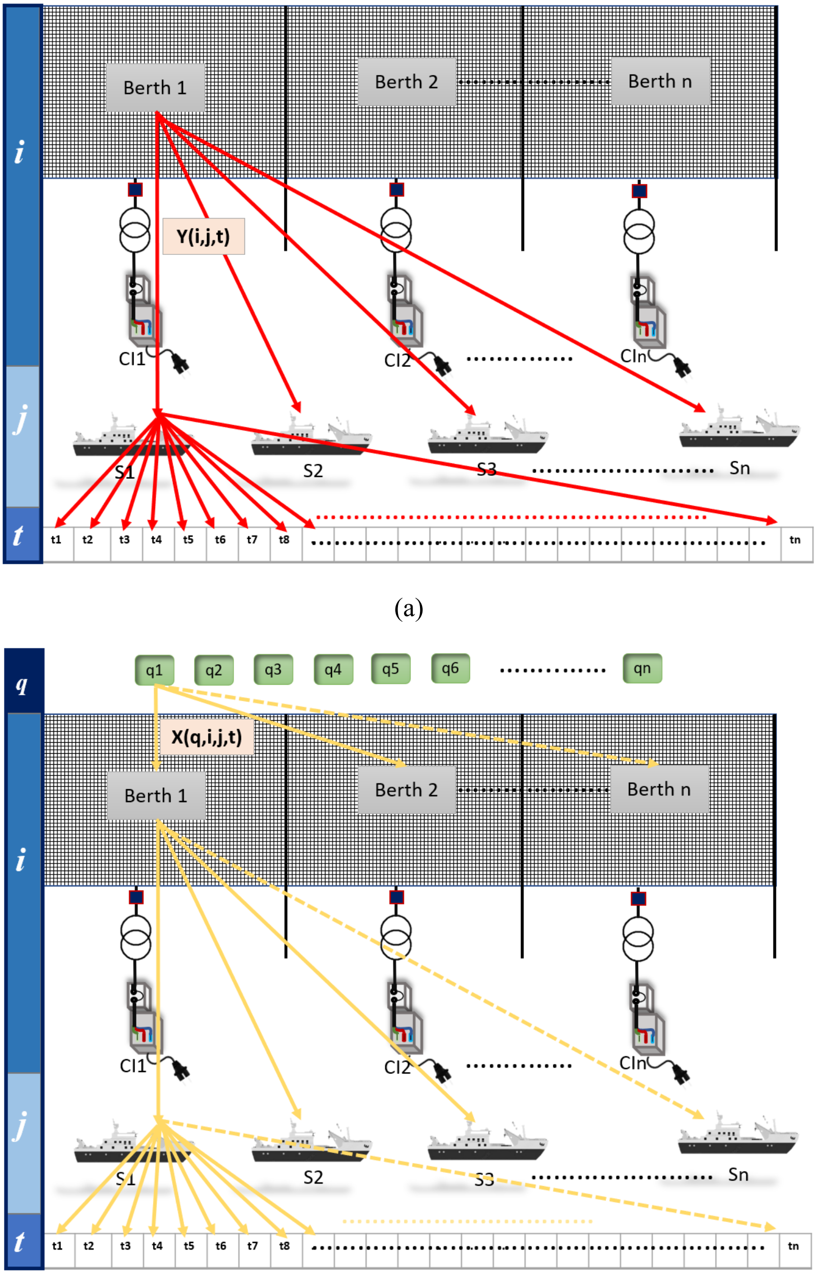


Fig. 3.5. The flow of activities by the ships as they approach the container port until their departure.

The port control room will receive data on the ships from shipping agents before the arrival of the ships, such as their arrival time, power needs, cargo volume, and expected departure time, which is indicated by due time in Fig. 3.5. It allows the implementation of a day-ahead strategy by collecting all information from berth stations and ships in advance. This data is managed via a port automation system that applies an optimization approach for three scheduling tasks of the BAP, CIAP, and QCAP to assign the ship to the suitable and available berth areas and handle their operation. Fig 3.6(a) and Fig. 3.6(b) show all the indexes used in this model to perform the BAP, CIAP, and QCAP scheduling. Arriving ships are first assigned to a berth station with sufficient capacity for cold ironing to meet the ship's power requirements. This is followed by the assignment of quay cranes to ensure that the cargo handling is completed before the due time.



(a)

(b)

Fig. 3.6. Port operation for (a) berth and cold ironing assignment and (b) quay crane assignment.

3.5.2. Optimization model for BAP, CIAP, and QCAP scheduling

The following assumptions have been applied to the optimization model developed in this study:

1. Each berth can only accommodate one ship at a time.
2. All container ships that arrive at the port use the cold ironing facilities for their onboard load while they are in berthing mode.
3. There are no constraints on the ship's dimensions (length, width, and depth).
4. The shore power is not provided at the anchorage area.

The detailed nomenclature used in this section for the variables involved is as follows:

Nomenclature

Sets			
Q	Set of active quay cranes in a container terminal, Q= {1,2,…12}	CI_i	Cold ironing capacity installed at berth *i*
B	Set of berths in a container terminal, B = {1,2,3}	qcb_i^{max}	The maximum number of quay cranes that can serve ship j at berth *i*
S	Set of ships to be served, S = {1,2,3,4,5}	P_q^{qc}	The power demand of quay crane *q*
T	Set of time intervals with 1-hour time step, T = {1,2…24}	ε_q^{qc}	Handling efficiency of the quay crane *q*
Scalar		ρ_q^{qc}	Individual load rating of the quay crane *q*
QC^{lim}	Total number of active quay cranes that can operate simultaneously at each time step	**Binary variables**	
Indices		y_{ijt}	1, if berth i is occupied by ship *j* at time *t*; 0, otherwise
q	Index of quay crane, $q \in$ Q	s_{jt}	1, if ship j starts berthing at time *t*; 0, otherwise
i	Index of berth, $i \in$ B	c_{jt}	1, if ship j is connected to a berth for cold ironing and handling operation at time *t*
j	Index of the ship, $j \in$ S	x_{qijt}	1, if quay crane q is assigned to the berth i to serve the ship *j* at time *t*; 0, otherwise
t	Index of time, $t \in$ T	**Integer variables**	
Parameters		wd_j	Waiting duration of ship *j* at anchorage in hours
at_j	Arrival time of ship j at port		
dt_j	Due time of ship j to depart from the terminal	hd_j	Handling duration of ship *j* at berth i in hours
P_j^{aux}	Auxiliary power required by ship j	st_j	Starting time of ship *j* for handling operation
qcs_j	The workload of the quay cranes to serve ship j for cargo handling	et_j	End time of ship *j* for handling operation

The optimization aims to minimize the total staying duration of ships at the port. Thus, the objective function is defined as follows:

$$min \sum_{j\in S} wd_j + hd_j \quad \forall j \in S \tag{3.1}$$

where the waiting and handling duration of the j^{th} ship at the port terminal are denoted by the first and second terms of (3.1). The equation is extended in (3.2). During the handling time window, the ship is connected to the cold ironing facility to get the electricity for their onboard load and allow the ship's auxiliary engines to be turned off. Subsequently, a set of quay cranes is allocated to serve the ship.

$$min \sum_{j\in S}(st_j - at_j) + (et_j - st_j + 1) \quad \forall j \in S \tag{3.2}$$

Berth Allocation Problem

The BAP constraints are presented in (3.3) to (3.11). A maximum of one ship can occupy each berth at any given time, according to constraint (3.3). When the ship is in an idle mood at anchorage and waiting to be allocated, the ship is not assigned to any berth. Meanwhile, the constraint (3.4) is to ensure that each ship at each time step can only be assigned to at most one berth. Constraint (3.5) indicates that the starting time for the ship' handling operation at berth can only start after the arrival time. Constraint (3.6) prevents the ship from having more than one start time, and the start time must occur within the 24-hour time frame specified in constraint (3.7). Constraints (3.8)-(3.9) prohibit the ship from being assigned a berth before its arrival time and after its due time to depart from the port. Constraints (3.10) describe the end time for the ship's handling operation, where the completion time for each ship must be before the due time to avoid disrupting the following berth allocation. Hence, leaving after the provided due hour is forbidden. Constraint (3.11) shows the relationship between the start time, berthing duration, and the end time for each ship.

$$\sum_{j\in S} y_{ijt} \leq 1 \quad \forall i \in B, \forall t \in T \tag{3.3}$$

$$\sum_{i\in B} y_{ijt} \leq 1 \quad \forall j \in S, \forall t \in T \tag{3.4}$$

$$st_j \geq at_j \quad \forall j \in S \tag{3.5}$$

$$\sum_{t\in T} s_{jt} = 1 \quad \forall j \in S \tag{3.6}$$

$$st_j = \sum_{t\in T} t.s_{jt} \quad \forall j \in S \tag{3.7}$$

$$\sum_{t=1}^{at_j} y_{ijt} = 0 \quad \forall i \in B, \forall j \in S \tag{3.8}$$

$$\sum_{t=dt_j}^{24} y_{ijt} = 0 \quad \forall i \in B, \forall j \in S \tag{3.9}$$

$$et_j \le dt_j \quad \forall j \in S \tag{3.10}$$

$$et_j = st_j + \sum_{t\in T}\sum_{i\in B} y_{ijt} - 1 \quad \forall j \in S \tag{3.11}$$

Cold ironing assignment problem (CIAP)

Constraints (3.12)-(3.19) outline the algorithms to assign suitable cold ironing to incoming ships and the operational constraints between the berth assignment, y_{ijt} and the ship connection, c_{jt}. Constraint (3.12) guarantees that the cold ironing capacity at the berth assigned to serve the ship *j* can meet the auxiliary power requirements of the ship. Constraints (3.13)-(3.14) are important to prevent interruptions during the handling period until the task is completed. Once berthed, the ship should remain at the same berth terminal until the end of operation. Only then, the ship is allowed to disconnect from the cold ironing and leave the port. Constraints (3.15)-(3.19) show the relationship between the connection time of the ship at the berth and the starting time of the handling operation. According to these equations, once the ship is connected to the berth, the handling operation will begin, and the starting time will be counted.

$$\sum_{j\in S} P_j^{aux}.\, y_{ijt} \le CI_i \quad \forall i \in B, \forall t \in T \tag{3.12}$$

$$y_{ijt} - y_{ijt-1} - c_{jt} + c_{jt-1} \ge -2 \quad \forall i \in B, \forall j \in S, \forall t > 1 \tag{3.13}$$

$$y_{ijt} - y_{ijt-1} + c_{jt} + c_{jt-1} \le 2 \quad \forall i \in B, \forall j \in S, \forall t > 1 \tag{3.14}$$

$$s_{j1=}c_{j1} \quad \forall j \in S \tag{3.15}$$

$$c_{jt} - c_{jt-1} \le s_{jt} \quad \forall j \in S, \forall t > 1 \tag{3.16}$$

$$c_{jt} - c_{jt-1} - 2.\, s_{jt} + 1 \ge 0 \quad \forall j \in S, \forall t \in T \tag{3.17}$$

$$\sum_{i\in B} y_{ijt} - c_{jt} = 0 \quad \forall j \in S, \forall t \in T \tag{3.18}$$

$$\sum_{t\in T}\sum_{i\in B} y_{ijt} - \sum_{t\in T} c_{jt} = 0 \quad \forall j \in S \tag{3.19}$$

Quay Cranes Assignment Problem (QCAP)

Constraints (3.20)-(3.28) are developed for the quay cranes assignment problem (QCAP). The new index *q* is introduced to define the unit for the quay crane, and x_{qijt} represents the binary decision for the quay crane assignment. Specifically, constraint (3.20) is to make sure that each quay crane at each time step can at most serve at one berth and one ship. Constraint (3.21) confirms that the quay crane can serve ship *j* at berth *i* only if ship *j* is assigned to berth *i*. The total number of active quay cranes that serve the ship *j* at berth *i* must be at least one unit of quay crane as defined in (3.22).

However, each berth terminal has a space limitation for the quay crane placement. To avoid a space conflict, the assigned quay cranes must be within the upper bound of the maximum number permitted in each berth as described in constraint (3.23). In addition, to avoid rail congestion, the port terminal can allow up to QC^{lim} number of quay cranes to operate simultaneously at each time step. This constraint is formulated in constraint (3.24).

$$\sum_{j\in S}\sum_{i\in B} x_{qijt} \leq 1 \quad \forall q \in Q, \forall t \in T \tag{3.20}$$

$$x_{qijt} \leq y_{ijt} \quad \forall q \in Q, \forall i \in B, \forall j \in S, \forall t \in T \tag{3.21}$$

$$\sum_{q\in Q} x_{qijt} \geq y_{ijt} \quad \forall i \in B, \forall j \in S, \forall t \in T \tag{3.22}$$

$$\sum_{j\in S}\sum_{q\in Q} x_{qijt} \leq qcb_i^{max} \quad \forall i \in B, \forall t \in T \tag{3.23}$$

$$\sum_{j\in S}\sum_{i\in B}\sum_{q\in Q} x_{qijt} \leq QC^{lim} \quad \forall t \in T \tag{3.24}$$

Constraint (3.25) ensures that once the ship is connected to the berth, the quay cranes' cargo handling workload must be met. The assigned number of quay cranes must at least equal the demanded number of quay cranes by the ship. These numbers vary with the cargo volume carried by the container ship in unit twenty-foot equivalent (TEU). Huge quantities of cargo tend to demand more quay cranes during the handling period. This constraint will also impact the berthing duration, as more quay cranes assigned accelerate the process of handling and fewer quay cranes are contrary.

$$\sum_{t\in T}\sum_{i\in B}\sum_{q\in Q} x_{qijt} \geq qcs_j \quad \forall j \in S \tag{3.25}$$

Time-invariant constraints used in this model are expressed in (3.26)-(3.27). It shows the relationship between the quay crane assignment and the ship's connection time at berth. This model uses binary variable x_{qijt} to indicate the status of quay crane q if it is assigned to berth i to serve ship j at time t. Constraints (3.26)-(3.27) must be satisfied to guarantee that the quay crane assigned to berth position i for ship j remains at the same berth until the handling operation is completed. It can't be interrupted during the period, and the quay crane can't change to another berth position until the handling process is complete. As the quay crane devices used in this study are the electric type of quay cranes, constraint (3.28) shows the calculation for the power demand from each quay crane. In this case, the power demand of the quay crane is obtained by multiplying the quay crane q with the handling efficiency and individual load rating.

$$x_{qijt} - x_{qijt-1} - c_{jt} + c_{jt-1} \geq -2 \quad \forall q \in Q, \forall i \in B, \forall j \in S, \forall t > 1 \tag{3.26}$$

$$x_{qijt} - x_{qijt-1} + c_{jt} + c_{jt-1} \leq 2 \quad \forall q \in Q, \forall i \in B, \forall j \in S, \forall t > 1 \tag{3.27}$$

$$P_q^{qc} = \varepsilon_q^{qc} . \rho_q^{qc} . x_{qijt} \tag{3.28}$$

Comparative model A

The performance of the proposed approach is compared to the scheduling model A in [6] as a benchmark model. In this model, the BAP is evaluated by integrating the cold ironing assignment at various capacities and modeling a fixed number of quay cranes at each berth in each time step. The quay crane in this model is not a decision variable. Thus, the quay crane didn't have any impact on the berthing duration. In this case, the berthing duration is formulated by using constraint (3.29), and its length is influenced by the berth availability and cold ironing constraint in (3.12).

$$\sum_t \sum_j y_{i,j,t} = dt_j - at_j + 1 \quad \forall j \in S \tag{3.29}$$

In contrast, the proposed model formulates berthing duration differently in (3.3)-(3.27) which corresponds to the QCAP's time-invariant technique. It distinguishes the waiting time and handling time when the handling time varies depending on the number of quay cranes allocated during the handling duration.

3.5.3. Terminal layout and data

The container terminal configuration implemented in the simulation has three berth areas with different cold ironing capacities and quay crane constraints. Fig. 3.7 shows the layout of the seaside terminal container. There are three different sizes of cold ironing capacities available such as small (1 MW), medium (1.5 MW), and large (2.0 MW). Every berth zone is allowed to assign a maximum of qcb_i^{max} quay cranes at each time step due to limitations on space. Table 3.1 provides the berth data and Table 3.2 summarizes the ship information.

The emissions of ships during berthing operations are calculated as follows:

$$TE_\sigma = \varepsilon_\sigma . E \quad \forall \sigma \tag{3.30}$$

where TE_σ represents the total emission of each pollution gas σ belonging to CO_2, NO_X, SO_2, and PM. It is calculated by multiplying the coefficient factor of ε_σ (g/kWh) with the amount of energy used, E (kWh). Table 3.3 lists the coefficient value used for each polluting gas.

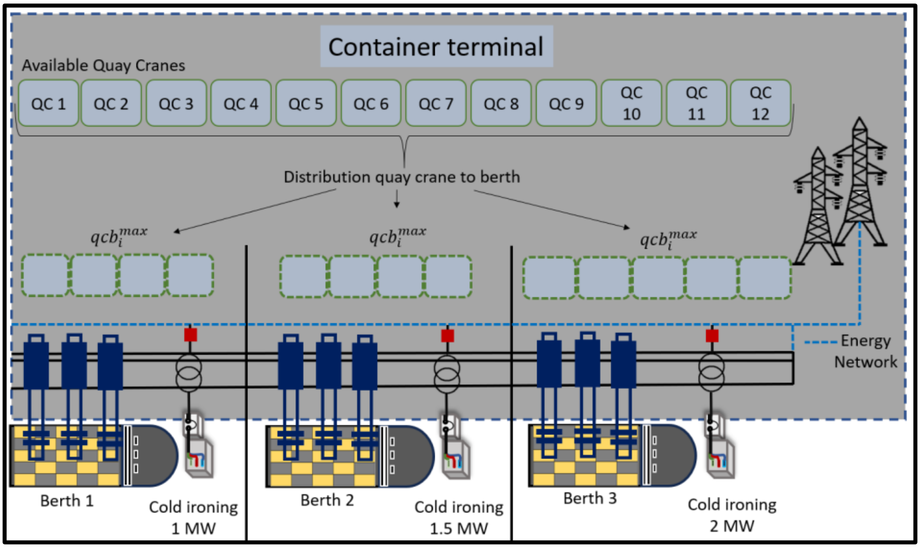


Fig. 3.7. Container terminal layout for the seaside operation.

Table 3.1. Berth information.

Berth i	Cold ironing capacity (MW) CI_i	The maximum number of quay cranes that can be assigned at each berth qcb_i^{max}
1	1	3
2	1.5	3
3	2	3

Table 3.2. Ship information.

Ship j	Arrival time at_j	Due time dt_j	Ship auxiliary power [MW] P_{jaux}	Required quay cranes to serve ship j qcs_j
S1	3	8	0.7	8
S2	4	10	0.7	12
S3	8	15	1.8	18
S4	9	15	1.26	14
S5	12	20	1.99	20

Table 3.3. The coefficient values used for the emission analysis [58]-[59].

Sources	Emission coefficients (g/kWh)			
	NOx	SO2	CO2	PM
MDO (0.5% sulfur)	13.9	2.12	692	0.38
Utility grid	0.32	0.07	426	0.03

3.6. Simulation results and discussion

3.6.1. Seaside operation scheduling

In this section, the performance of the proposed optimization strategy for integrated scheduling at a container terminal is compared with Model A as the benchmark. Fig. 3.8 and Table 3.4 present the results of seaside operation scheduling for ships S1-S5 obtained from the proposed model and model A. It can be observed that integration of cold ironing into the port energy system by using the proposed model significantly reduces ship stay duration compared to model A. Model A experiences a longer stay (41 hours) with a 4-hour wait for ship S5. The different cold ironing service capacities at berths influence berthing positions, causing delays. The analysis reveals that S5's 4-hour delay is due to its high-power demand that is only suitable to berth at berth 3. The limited space allows only one ship at a time, necessitating S5 to wait for S3 to depart before it can start berthing.

The proposed algorithm demonstrates a noteworthy 58.54% reduction in ship stay duration at the port, decreasing from 41 to 17 hours. Berth allocation incurs zero waiting time, allowing immediate assignment upon ship arrival. Handling durations are also optimized, ranging from 2 to 4 hours for ships S1-S5. Fig. 3.8(b) visually represents the efficient handling timeframe for the proposed method. This reduction in handling time minimizes delays in subsequent ship assignments of BAP, contributing to an overall shorter ship's stay at port.

Apart from BAP, the other vital scheduling is CIAP and QCAP. Accordingly, after the ship has been assigned to a berth, cold ironing allocation should be made followed by scheduling quay cranes. It can be observed that cold ironing is assigned following the correct size for each ship, ensuring uninterrupted energy supply to the ships' onboard loads throughout handling. The simulation analysis findings underscore that the substantial reduction in handling duration is primarily attributed to the effective scheduling of quay cranes that execute the QCAP time-invariant approach.

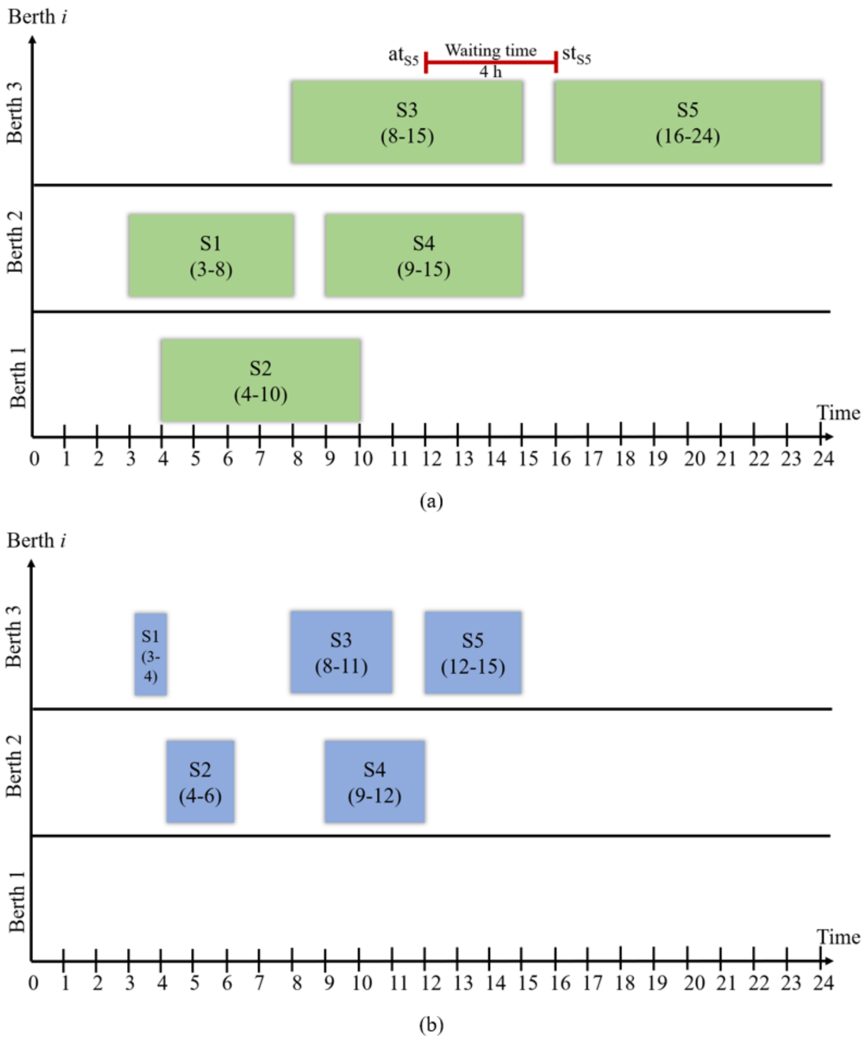


Fig. 3.8. Berth scheduling result for (a) benchmark model and (b) proposed model.

Fig. 3.9 illustrates the outcomes of time-invariant QCAP scheduling, where each crane remains dedicated to the same ship until its cargo handling is complete to minimize the quay crane movement. Movement between berths only occurs during long time gaps between ship handling activities as can be seen from Q3 and Q6.

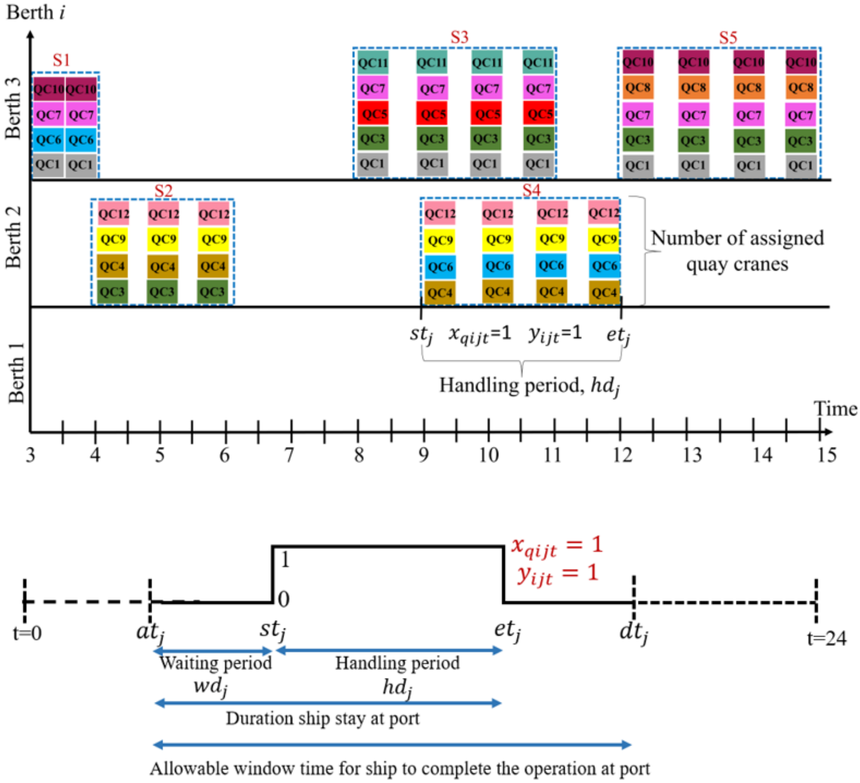


Fig. 3.9. The result of time-invariant quay crane scheduling.

The analysis also highlights the correlation between the number of assigned quay cranes and faster handling, allowing more cranes for ships with larger cargo volumes. This differs from model A, which employs a fixed quay crane assignment regardless of cargo size, potentially causing delays for larger shipments. The simulation indicates that managing port resources through optimization algorithms for various seaside operations (BAP/CIAP/QCAP) effectively reduces waiting durations. This optimization approach proves more practical, immediate, and cost-effective compared to facility upgrades. The results align with prior research [55], emphasizing the effectiveness of the proposed optimization technique in enhancing port operation performance.

3.6.2. Assessment of energy saving

In terms of energy consumption on the seaside, cold ironing facilities and quay cranes are the primary devices. Fig. 3.10 depicts their energy profiles during handling, with the peak demand occurring between 9:00 a.m. and 12:00 p.m. Cold ironing consumes more energy than quay cranes, dependent on factors like ship power usage, arrival

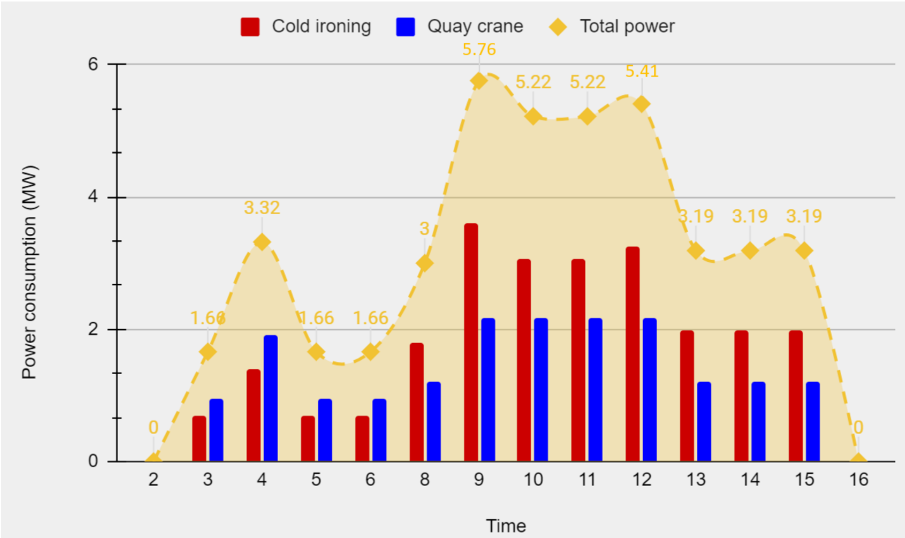


Fig. 3.10. Energy profile during the handling period.

Table 3.4. Comparison of the benchmark model and the proposed model (cold ironing (CI), quay crane (QC)).

Evaluation aspect	Total stay duration of ship at port (h)	Total handling period (h)	Total waiting period (h)	Total CI energy consumption (MWh)	Total QC energy consumption (MWh)	Total CI energy cost (€)	Total QC energy cost (€)
Benchmark model	41	37	4	50.23	26.64	10568.39	5605.06
Proposed model	17	17	0	24.24	18.24	5100.10	3837.70

frequency, berthing duration, and ship size. Quay cranes, the second-largest energy consumers during seaside operations, exhibit higher consumption than cold ironing at certain hours, influenced by the number of assigned cranes.

The energy assessment analysis aims to evaluate the impact of the proposed scheduling strategy on port energy demand. Integration of cold ironing in port increases terminal power consumption, necessitating efficient energy management. Table 3.4 summarizes energy costs and consumption, revealing 51.74% and 31.53% reduction in cold ironing and quay crane energy consumption obtained from the proposed model compared to model A. As a result, the port operator stands to gain significantly from a substantial reduction in energy costs, decreasing from €10,568.39 to €5,100.10 for cold ironing and from €5,605.06 to €3,837.70 for quay crane operations. This reduction translates to substantial cost savings for the port operator, aligning with a study in [60] indicating that reducing port call duration can lead to considerable energy savings.

3.6.3. Assessment of the environmental impact

Given that the main purpose of cold ironing is to alleviate pollution from ships' operations, a comprehensive environmental examination is essential to ascertain the greatest potential of the proposed optimization technique in reducing emissions at the port. In this context, the impact on emission reduction is assessed by analyzing the waiting duration and handling duration of ships, as both factors collectively represent the overall duration of ships' stay at the port from arrival to departure.

Table 3.5 presents emission results from seaside operation scheduling using both the benchmark and the proposed model. The proposed model eliminates ship emissions during waiting, while the benchmark model results in emissions of 110.64kg of NOx, 16.88kg of SO2, 5508.32kg of CO2, and 3.03kg of PM, primarily due to a 4-hour wait for ship S5. In anchorage, ships do not have access to the cold ironing facility, thus their auxiliary engines are running to supply their onboard load. This emphasizes the significance of cold ironing in emissions reduction at ports, as ships at anchor rely on auxiliary engines burning 0.5% marine diesel oil (MDO).

The proposed approach not only improves port performance by reducing the waiting durations but also significantly cuts emissions during handling. Compared to the benchmark model, it successfully reduces 8.3kg of NOx, 1.82kg of SO2, 11071.74kg of CO2, and 1.52kg of PM. The reduction in berthing time lowers the demand for cold ironing energy, contributing to emission reduction. The time-invariant QCAP optimally assigns quay cranes, further expediting the process. This highlights the promising potential of the proposed approach in minimizing emissions during both waiting and handling durations at container ports. These findings emphasize the role of ship stay duration in achieving carbon footprint goals and reducing energy consumption and emissions.

Table 3.5. The emission reduction results of the proposed approach.

Gases of emission	Emissions (kg)					
	Waiting interval		Handling interval		Total emission	
	Benchmark model	Proposed model	Benchmark model	Proposed model	Benchmark model	Proposed model
NO_x	110.64	0	16.07	7.76	126.71	7.76
SO_2	16.88	0	3.52	1.70	20.4	1.70
CO_2	5508.32	0	21397.98	10326.24	26906.3	10326.24
PM	3.03	0	1.51	0.73	4.54	0.73

3.7. Summary of the contribution

(1) Proposing a MILP optimization framework to efficiently synchronize three crucial scheduling tasks within seaside operations: BAP, CIAP, and QCAP. The developed mathematical algorithm showed how the port resources (berth, cold ironing, and quay cranes) engage with the BAP and how they can be used efficiently.
(2) Addressing the significance of implementing a time-invariant strategy for QCAP to effectively coordinate the quay crane's port resources. Implementing this technique complements optimized berth allocation in the optimization model and highlighted its potential to accelerate cargo handling, avoid severe ship delays for berth allocation, and effectively eliminate wasteful crane relocations.
(3) Investigating the integrated operation of BAP, CIAP, and QCAP from an economic and environmental standpoint.

3.8. Conclusion

In this chapter, the optimization strategy for the seaside operations of container terminals was investigated, by considering three different scheduling problems BAP, CIAP, and QCAP. The proposed cooperative MILP optimization efficiently using berths, cold ironing, and quay cranes and improves the port performance by significantly reducing ships' overall stay duration. This coordination strategy is helpful especially when resources are limited, avoiding costly facility upgrades. It is practical, simple to implement, and suitable for immediate deployment with automated monitoring in port control rooms. Simulation analyses also highlighted the crucial impact of ships' stay duration on energy, and emissions aspects. Reducing this duration substantially decreases energy needs for cold ironing and quay cranes, lowering pollutants and energy costs. The time-invariant QCAP strategy plays a crucial role in accelerating the loading/unloading process for berthed ships, thereby minimizing their stay duration.

However, the study has limitations, particularly the main reliance on the local grid network for cold ironing. It can be observed from the result that cold ironing integration demands a considerable amount of energy. In real practice, some situations might stimulate higher energy demand, potentially putting pressure on the port's existing energy network. In this case, coordinating with microgrid concepts, leverages mixed energy sources for more flexible and cost-effective energy scheduling. Additionally, integrating renewable sources can enhance the emission neutrality of the cold ironing systems, making the proposed cooperation more appealing for execution at ports. This concept will be investigated in depth in the next chapter.

Chapter 4. Seaport microgrid energy management system with integrated cold ironing

4.1. Introduction

Emerging the cold ironing systems at port introduces new adaptations to port handling processes, as discussed in Chapter 3. Another challenge that needs to be addressed is the large electricity demand for cold ironing systems to power multiple incoming ships, burdening the aging energy infrastructure of ports.

Ports comprise heavy electrical loads operating continuously across extensive machinery, buildings, transportation, and lighting systems. Integrating additional power-consuming systems of cold ironing further pressures on the existing port energy network, with each berthed ship potentially demanding megawatts of shore power [61]. Prior work found in [43] emphasizes that simply integrating cold ironing as an uncoordinated added load will impose a substantial load burden on the terminal. Accordingly, recent studies have analyzed coordinating cold ironing with locally generated microgrid power as a promising approach to alleviate grid pressures [62] [63]. The promising findings in this microgrid energy incorporation inspire the concept presented in this chapter for seaport microgrid integration.

Synchronizing complex seaside operations scheduling of BAP, CIAP, and QCAP for arriving ships with energy scheduling of seaport microgrid poses management challenges as it is two different scheduling problems with an interacting process. The conflicting objectives between these two scheduling problems and constraints across berthing, cold ironing, cranes, and microgrid control require a reliable and effective strategy. Hence, this research proposes an energy management system integrating maritime electrification technologies of seaport microgrids and cold ironing through a two-level optimization framework. By concurrently optimizing operational logistics and microgrid dispatch, ports can integrate sustainability initiatives of cold ironing technology while maintaining port performance, optimally dispatching the energy, and enhancing cost-efficiency. Fig. 4.1, visualizes the port energy management strategy and its importance.

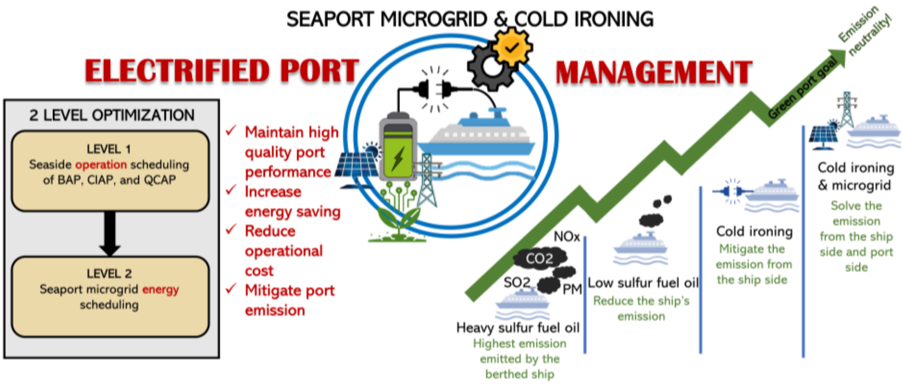


Fig. 4.1. Port energy management strategy at the seaside operation of a container terminal.

4.2. Seaport microgrid and cold ironing

The dynamic load of the berthed ships due to varied traffic patterns with continuous ships coming in and out of a port potentially demands cold ironing capacity of up to MVA level calling attention to energy security and reliability. The cold ironing's high-power demand due to the heavy ship traffic or arrival of multiple large ships with huge auxiliary power demand at once can be harmful to existing port energy networks and disrupt ongoing port operations. Also, in case there is a fault in the upstream network, the power supply to the port will be interrupted. Seaport microgrids capable of islanded operation can stabilize shore power supply when the main grid deteriorates, securing cold ironing continuity. Besides, the port operator is a profit-driven entity demanding low operation costs. Seaport microgrids with diverse assets of renewable generators, energy storage, and grid interconnection enable flexible and cost-optimal dispatch to serve variable cold ironing needs. Fig. 4.2 shows the coordination of cold ironing and the seaport microgrid system. An energy management strategy can optimally control the generation units, manage the consumption from different port activities, and handle the interaction with the power grid to support efficient electrification.

Maritime stakeholders are actively exploring microgrid integration into their energy system configuration with many existing and ongoing efforts. Among them is the Port of Vigo which established 100 kW of solar and wind power for their local load, the Port of Barcelona providing 75% of their berthed ships' power from wind and 25% from solar, and the Port of Civitavecchia distributing 2 MW of solar resources for their port buildings [64].

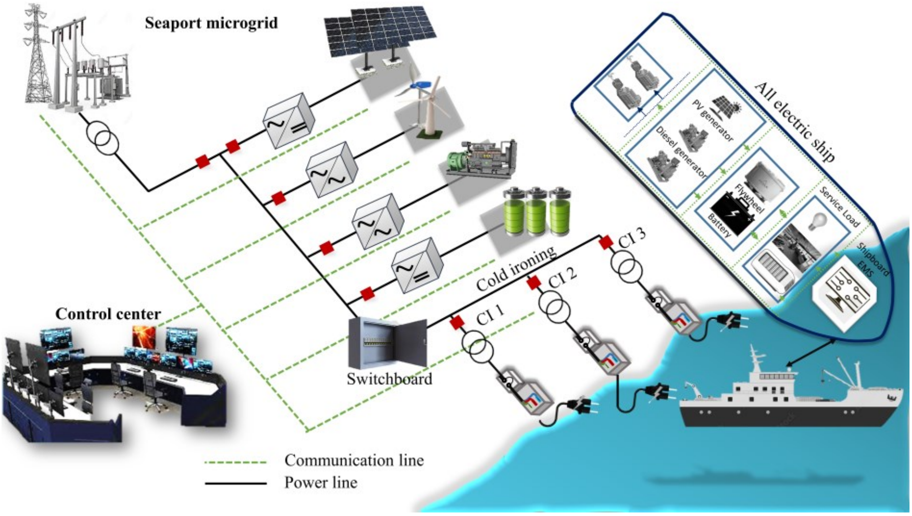


Fig. 4.2. Seaport microgrid and cold ironing.

Recent literature shows an increasing trend of research interest in exploring diverse electricity alternatives for providing stable cold ironing services. In [43], a proposed microgrid system effectively mitigates peak load from berthed ships powered by cold ironing, resulting in a significant reduction in daily peak load and associated energy costs. Another work by Yue Zhang et al. [18] introduces an optimization framework for a port microgrid responding to dynamic power consumption and intermittent renewable power to supply cold ironing power demand. This approach enhances the flexibility and self-sufficiency of the port energy system, leading to a substantial 7.6% reduction in operational costs. Additionally, a study in [65] employs the microgrid concept to attain emission neutrality in integrated cold ironing activities.

The proven benefit of the microgrid concept with the cold ironing motivates the integration of a seaport microgrid in this study. However, seaport microgrid employment poses challenges regarding port environments, port operational complications, and integration with dynamic logistics. Extensive coordination, planning, and optimization are imperative to strategically coordinate microgrids into port operations.

4.3. Port operation and energy management

Fig 4.3 shows different operation management aspects encountered by the port operator comprising both the operation side and the energy side. The three different seaside operation problems requiring coordination are BAP, CIAP, and QCAP to allocate berth position, assign sufficient shore power, and schedule the quay crane to arriving ships at the port.

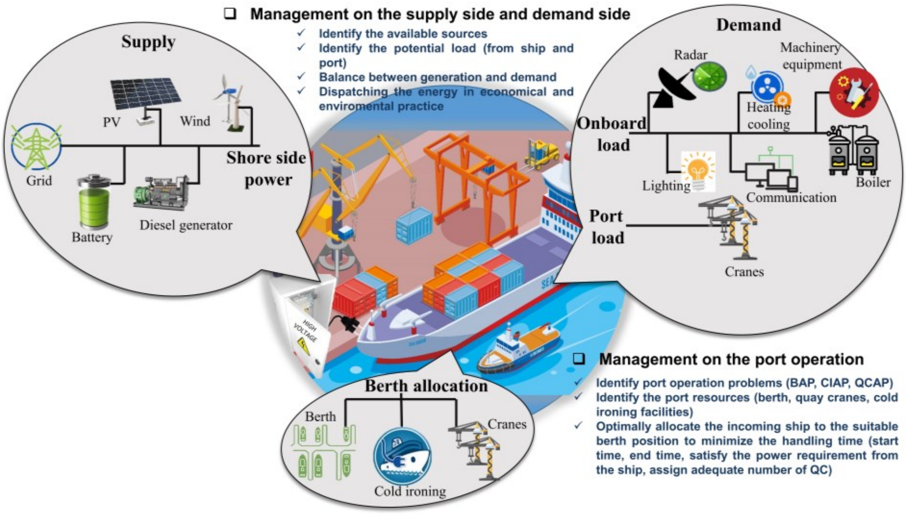


Fig. 4.3. The management aspects of the seaside operation at the port during berthing mode.

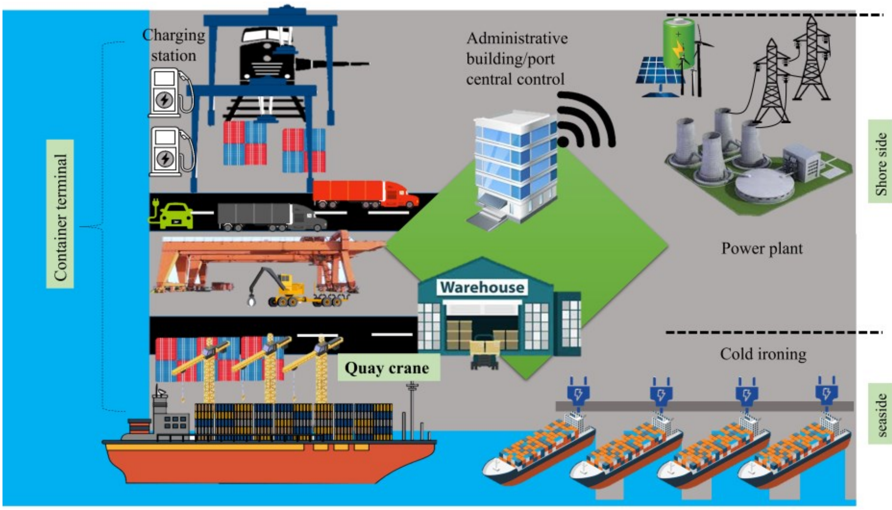


Fig 4.4. Port resources and operations at the seaside and shoreside

Fig 4.4 illustrates the port resources and operations involved in the seaside region. BAP and CIAP exhibit mutual dependence as the berthing duration impacts the energy consumption of cold ironing. Various cold ironing services come with different capacities, requiring an appropriate BAP to fulfill the power needs of the berthed ships. Likewise, a strong correlation exists between BAP and QCAP, with the number of assigned quay cranes influencing the handling duration [57]. The cooperative scheduling between these problems adds more constraints in the problem formulation which makes the scheduling problem complex and hard to tackle.

The integration of microgrid systems with port operations exhibits promise, but there are still some knowledge gaps between the energy and operational domains. To address the intricate interrelations between seaside operational and energy scheduling problems, an effective port management system with good coordination is needed. In a competitive maritime business, integrated solutions are essential for improving port performance, and economic, environmental, and energy issues. Bridging these gaps, this thesis proposes an integrated two-level optimization framework coordinating between the seaside operational scheduling and the energy scheduling problems.

4.3.1. Two-level optimization framework for energy management of seaport microgrid

Fig. 4.5 shows the proposed two-level optimization framework designed for an electrified container terminal. This framework effectively coordinates the seaside operation scheduling problem and the energy scheduling problem of the seaport microgrid. The first level focuses on three seaside operation scheduling problems BAP, CIAP, and QCAP. The model executed at this level applies the model proposed and validated in Chapter 3. The goal is to enhance service performance by minimizing ship stay times by reducing berthing durations and handling time. Consequently, decreasing cold ironing and quay crane electricity consumption.

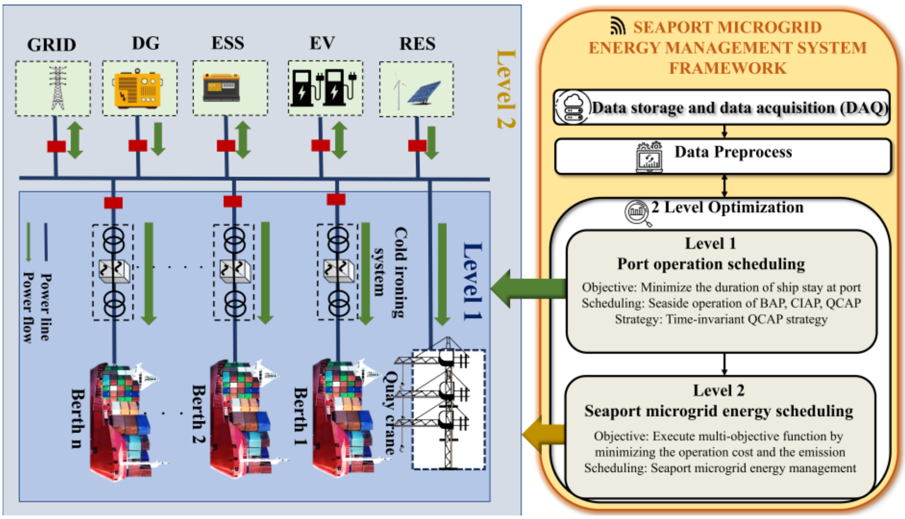


Fig. 4.5. The proposed two-level optimization model for electrified seaside port operation.

The second-level optimization is dedicated to optimal microgrid energy management by strategically coordinating diverse assets. Port operators, driven by both profit motives and environmental regulations, seek to balance economic and sustainability objectives. Thus, a multi-objective function is designed for minimizing port operation costs and emissions. The proposed architecture incorporates renewable sources, dispatchable diesel generators, energy storage systems, electric vehicles, and utility interconnection. Operational data from the first level informs the second level on microgrid load profiles. The integrated framework seamlessly aligns port operations with energy management to enhance port performance and minimize operation costs while evolving toward carbon neutrality objectives. GAMS optimization is employed to execute the system models and CPLEX is utilized as a solver.

The variables used in this section are defined as follows:

Nomenclature

Sets		$P_t^{dESS,min}$, $P_t^{dESS,max}$	Minimum and maximum discharging power of electric vehicle at time t
DG	Set of fuel generator units, DG = {1,2,3}	ε_{em}	The pollutant coefficient of CO2, SO2, NOx, and PM (g/kWh)
c	Set of counter, c={1,2,…Nc }	**Binary variables**	
k	Set of objective function in level-2 optimization, k={1,… N_{obj} }	c_t^{ESS}, d_t^{ESS}	1, if the ESS is charging/discharging state at time t; 0, otherwise
T	Set of time intervals with 1-hour time step, T = {1,2…24}	u_t^{grid}	1, if there is power draw from the grid at time t; 0, otherwise
Scalar		**Variables**	
$P_{grid_{buy}}^{Max}$, $P_{grid\_sell}^{Max}$	Maximum buying and selling power from the grid	$P_{g,t}$	Dispatchable power from DG unit g at time t
$SOE_t^{min\_ESS}$, $SOE_t^{\max\_ESS}$	Minimum and maximum state of energy from ESS	$P_t^{grid\_buy}$	Buying power from the grid at time t
$\eta_{c,ESS}$, $\eta_{d,ESS}$	ESS charging and discharging efficiency	$P_t^{grid\_sell}$	Selling power to the grid at time t
Indices		OF_1, OF_2	Objective functions 1 and 2 for Level-2 optimization problem
t	Index of time, t ∈ T	OF_k^{Max}, OF_k^{Min}	Maximum and minimum value objective function k
g	Index of dispatchable fuel generator unit, g ∈ DG	P_t^{pv}	Power from PV at time t
Parameters		P_t^{wt}	Power from WT at time t
a_g, b_g, c_g	Cost coefficient for dispatchable fuel generator g	$P_t^{d,ESS}$, $P_t^{c,ESS}$	Charging and discharging power from ESS at time t

$\alpha_g, \beta_g, \gamma_g$	Emission coefficient for dispatchable fuel generator g		
σ	Grid price (€/MWh)	l_t^{Port}	Total port load from the terminal, cold ironing, and quay crane at time t
RU_g, RD_g	Ramp up and ramp down dispatchable fuel generator g	$l_t^{Terminal}$	Terminal load demand at time t
P_g^{min}, P_g^{max}	Minimum and maximum power of dispatchable fuel generator g	l_t^{CI}	The cold ironing load demand at time t
$P_t^{pv,min}$, $P_t^{pv,max}$	Minimum and maximum power of photovoltaic at time t	l_t^{QC}	The quay crane load demand at time t
$P_t^{wt,min}$, $P_t^{wt,max}$	Minimum and maximum power of wind turbine at time t	SOE_t^{ESS}	State of energy for energy storage system at time t
$P_t^{cESS,min}$, $P_t^{cESS,max}$	Minimum and maximum charging power of energy storage system at time t	TE_{em}	Total emission each gas emission from CO2, SO2, NOx, and PM
$P_t^{dESS,min}$, $P_t^{dESS,max}$	Minimum and maximum discharging power of energy storage system at time t	E	The amount of energy used by the ship at port (MWh).

1) Level 1- Port operation scheduling

The first-level optimization coordinates multi-scheduling activities on the seaside port operation of BAP, CIAP, and QCAP. The problem formulations for the operation optimization are developed as a mixed-integer linear programming (MILP) model with linear objective functions subject to various equality and inequality constraints. The formulated objective function and seaside operation constraints are defined in (3.1) to (3.28) in Chapter 3.

2) Level 2- Seaport microgrid energy scheduling

The second-level optimization is executed in a broader perspective that tackles the energy problem of the seaport microgrid. It schedules both dispatchable and non-dispatchable generator units, battery, and coordinates power transactions with the main grid. Using the operational outcome from level one, the microgrid is controlled to serve port energy needs with cost-effectively and sustainably. This optimization structure allows efficient coordination between port activities and microgrid resources.

A multi-objective optimization model is formulated to minimize microgrid operation cost (OF1) and emissions (OF2). The second-level microgrid optimization is formulated as a mixed-integer nonlinear programming (MINLP) model, capturing the complexities of multi-objective energy management. The mathematical expressions for both objective functions are as follows:

$$Min\{OF_1 = \sum_{t\in T}\sum_{g\in DG} a_g P_{g,t}^2 + b_g P_{g,t} + c_g + \sum_{t=1}^{24} P_t^{grid\_buy}\sigma - \sum_{t=1}^{24} P_t^{grid\_sell}\sigma\} \quad (4.1)$$

$$Min\{OF_2 = \sum_{t\in T}\sum_{g\in DG} \alpha_g P_{g,t}^2 + \beta_g P_{g,t} + \gamma_g \} \quad (4.2)$$

By integrating these two objective functions, a multi-objective optimization problem is defined in (4.3).

$$Min\ OF_k(x) \quad k = 1: N_{obj} \quad (4.3)$$

where $OF_k(x)$ indicates the k^{th} objective function and N_{obj} signifies the number of objectives, which is two in this model. Unlike single-objective problems, this multi-objective optimization generates a Pareto front of non-dominated solutions representing tradeoffs between cost and emissions. To select the best balance point, a fuzzy satisfaction method in [66] is applied as shown in (4.4).

$$\mu_k = \begin{cases} \frac{OF_k^{Max} - OF_k}{OF_k^{Max} - OF_k^{Min}} & F_k^{Min} \le F \le F_k^{Max} \\ 0 & Otherwise \end{cases} \quad (4.4)$$

Equation (4.5) is used to prevent severely compromising any single objective. This maximizes the minimum membership level to identify the solution providing the highest possible satisfaction across both objectives. The visualization empowers port managers to incorporate strategic priorities into the decision-making process.

$$\underset{c=1:N_C}{Max}(\underset{k=1:N_{obj}}{Min}\ \mu_k^c) \quad (4.5)$$

The energy scheduling in seaport microgrid is subject to various operational constraints defined in (4.6) to (4.19). Constraint (4.6) ensures power balance among the utility, dispatchable generator, renewables, and energy storage to meet the electricity demand of the port terminal. This includes requirements for cold ironing, crane load, and other port facilities, as specified in (4.7).

$$\sum_{g\in DG} P_{g,t} + P_t^{grid\_buy} + P_t^{res} + P_t^{d,ESS} = \sum_{l\in L} l_t^{Port} + P_t^{grid\_sell} + P_t^{c,ESS}\ \forall t \in T \quad (4.6)$$

$$l_t^{Port} = l_t^{Terminal} + l_t^{CI} + l_t^{QC} \quad \forall t \in T \quad (4.7)$$

The microgrid's deployable distributed generation units comply with power capacity limitations in (4.8), which govern the maximum and minimum limits on each generator's output. Furthermore, the dispatchable distributed generation units are limited by ramp-up and ramp-down limitations, which are represented in equations (4.9) and (4.10). It determines the permissible degree of a rise or drop in their output over time.

$$P_g^{min} \leq P_{g,t} \leq P_g^{max} \quad \forall t \in T, \forall g \in DG \tag{4.8}$$

$$P_{g,t+1} - P_{g,t} \leq RU_g \quad \forall g \in DG, \forall t < 24 \tag{4.9}$$

$$P_{g,t-1} - P_{g,t} \leq RD_g \quad \forall g \in DG, \forall t > 1 \tag{4.10}$$

The port microgrid interacts bidirectionally with the utility grid. Considering the physical constraints of the Point of Common Coupling (PCC), constraints (4.11) and (4.12) set the maximum and minimum energy exchange limits. The binary variable u_t^{grid} is utilized to enforce exclusive buying or selling of power at any given time. Additionally, constraints (4.13) and (4.14) define the generation limits for the renewable sources of photovoltaic and wind turbine units.

$$P_t^{grid\_buy} < u_t^{grid}.P_{grid\_buy}^{Max} \quad \forall t \in T \tag{4.11}$$

$$P_t^{grid\_sell} < \left(1 - u_t^{grid}\right).P_{grid\_sell}^{Max} \quad \forall t \in T \tag{4.12}$$

$$P_t^{pv,min} \leq P_t^{pv} \leq P_t^{pv,max} \quad \forall t \in T \tag{4.13}$$

$$P_t^{wt,min} \leq P_t^{wt} \leq P_t^{wt,max} \quad \forall t \in T \tag{4.14}$$

Constraints (4.15)-(4.19) specify the energy storage system operation. Energy storage in this system is to provide backup power and store surplus renewable generation. The intermittency of solar/wind and unshiftable port loads necessitate optimized storage to smooth fluctuations. The battery operates within charging/discharging power limits per (4.15)-(4.16) and prevents concurrent charging and discharging via (4.17). State of energy constraint (4.18) maintains longevity while (4.19) tracks the storage level.

$$P_t^{cESS,min} \leq P_t^{c,ESS} \leq P_t^{cESS,max}.c_t^{ESS} \quad \forall t \in T \tag{4.15}$$

$$P_t^{dESS,min} \leq P_t^{d,ESS} \leq P_t^{dESS,max}.d_t^{ESS} \quad \forall t \in T \tag{4.16}$$

$$c_t^{ESS} + d_t^{ESS} \leq 1 \quad \forall t \in T \tag{4.17}$$

$$SOE_t^{\min\_ESS} \leq SOE_t^{ESS} \leq SOE_t^{\max\_ESS} \quad \forall t \in T \tag{4.18}$$

$$SOE_t^{ESS} = SOE_{t-1}^{ESS} + \left(P_t^{c,ESS}\,\eta_{c,ESS} - \frac{P_t^{d,ESS}}{\eta_{d,ESS}}\right)\Delta t \quad \forall t \in T \tag{4.19}$$

4.3.2. Seaport layout and data

Numerical experiments are carried out in this section to demonstrate the potential of the proposed scheduling strategy. Fig. 4.6 visualizes the handling process at the container terminal from the ship's arrival until its departure. The parameters for the seaport microgrid and energy management system are provided in Table 4.1 and Table 4.2, respectively.

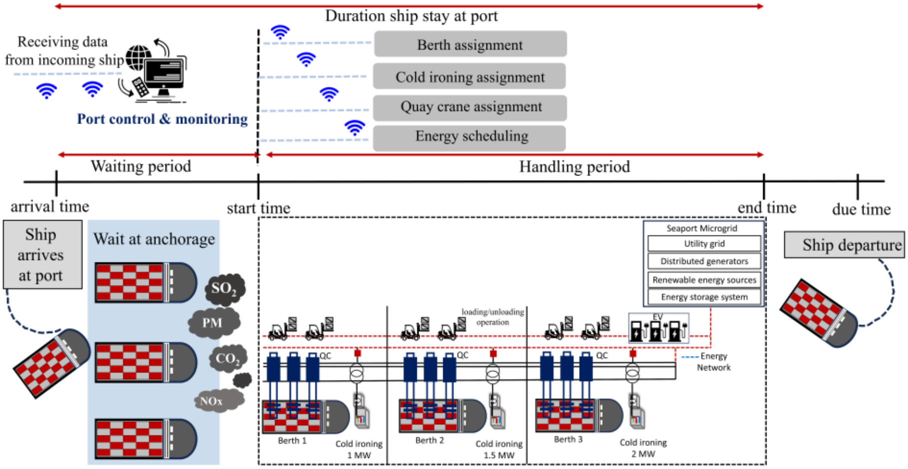


Fig. 4.6. Seaside operation scheduling and seaport microgrid energy scheduling.

Table 4.1. Parameter for seaport microgrid.

Parameter	Value	Unit
P_t^{pv}	0-13	MW
P_t^{wt}	1-15	MW
Δt	1	hour
T	24	hour
$SOE_t^{\max\_ESS}$	30	MW
$P_t^{c,d,ESS,max}$	0.2SOE	MW
$\eta_{c,d,ESS}$	87(90)	%

Table 4.2. Dispatchable generator units parameter [67].

DG	a	b	c	α	β	γ	P_g^{min} / P_g^{max} (MW)	RU_g / RD_g (MW)
1	0	1.5	0.0085	5.326	-3.550	3.380	2/6	2
2	0	2.0	0.0030	4.091	-5.54	6.490	2/7	2
3	0	2.5	0.0170	2.543	-6.047	5.638	2/8	2

The performance of the proposed scheduling approach is evaluated in comparison to the benchmark model of the fixed berth-quay crane scheduling approach from prior work [22] with consideration of a conventional port energy system. Regardless of the amount of cargo on each ship, this model assigns a fixed number of quay cranes per berth. Crane assignment is not a decision variable and handling time depends on cold ironing power constraints in (3.12).

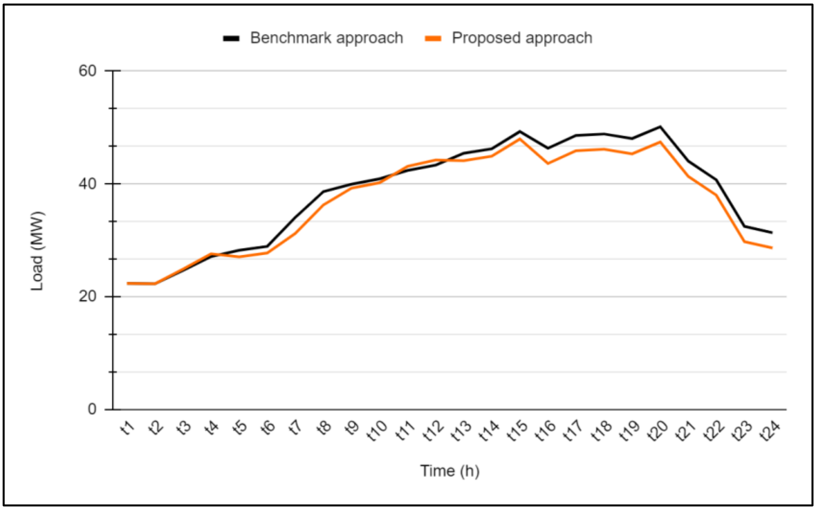
4.4. Simulation results and discussion

4.4.1. Energy scheduling

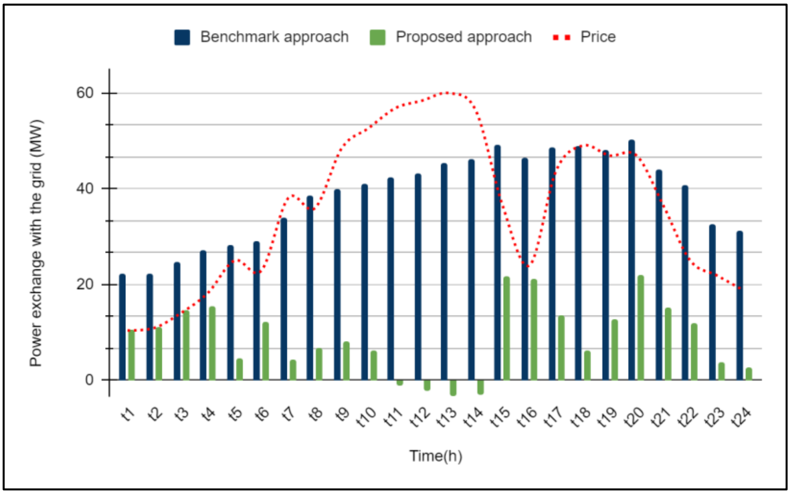
The energy assessment quantifies impacts on port demand and supply between the proposed integrated model and the benchmark model. Fig. 4.7 illustrates a comparison of the effects on load demand and grid energy between both models. The proposed seaside operation scheduling methods have a notable impact on the electricity consumption of cold ironing and quay cranes, contributing to the observed profile distinctions. Compared to the benchmark model, the integrated approach consistently achieves a significant reduction in both demand and grid power purchases.

The higher energy consumption identified in the benchmark method is attributed to the cold ironing capacity, impacting the assignment in the BAP. It also prolongs ship handling times due to a fixed number of quay cranes assigned per berth regardless of cargo volume. While this static crane assignment may suffice for smaller cargo ships, larger container ships experience substantial handling delays without sufficient cranes. In contrast, the proposed approach introduces a flexible, load-based crane assignment strategy, demonstrating its advantages.

The implementation of the proposed strategy results in a significant reduction in energy consumption, with a decrease of 52.82% for cold ironing and 31.53% for quay cranes compared to the benchmark approach. This reduction is credited to the enhanced performance of the proposed seaside operation scheduling, which speeds up the handling process while ensuring sufficient shore power for berthed ships. The time-invariant QCAP assignment method, implemented in Level-1 optimization, plays a crucial role by distributing handling assignments based on cargo volume and eliminating unnecessary crane movements. However, there is a temporary increase in consumption between t11 and t12 as two ships receive high shore-to-ship power and a higher number of active quay cranes. The higher allocation of quay cranes contributes to increased energy demand but reduces handling time. The outcome aligns with findings from previous research in [60] indicating energy savings with reduced port call duration, offering benefits to both port operators and ship owners in port performance, energy, financial, and emission aspects.



(a)



(b)

Fig. 4.7. The comparison of (a) the port load and (b) the power exchange with the grid for the benchmark and the proposed approach.

In addition, the load profile in Fig. 4.7(a) demonstrates that the proposed approach reduces maximum power demand from 50.16 MW to 47.45 MW. This reduction indicates that the proposed strategy manages to distribute loads more evenly over time. The decrease in peak demand quantifies the system's potential to better resource utilization and minimize infrastructure sizing requirements for the high shore power capacity installation, avoiding unnecessary investments. Although the current scenario exhibits a modest 2.71 MW reduction in a 5-ship and 24-hour setting, the

Table 4.3. Numerical result from the integrated optimization strategy.

Approach	Duration of ship stay at port (h)	Total handling duration (h)	Total waiting time (h)	Total port energy consumption (MWh)	Total cost of energy (€)	Cold ironing energy consumption (MWh)	Quay crane energy consumption (MWh)
Benchmark approach	41	37	4	924.84	3464.248	50.23	26.64
Proposed approach	17	17	0	889.91	1571.862	23.7	18.24

proposed scheduling can achieve more substantial peak-shaving effects when applied to larger ports and ships.

From the power distribution perspective, the benchmark approach has a higher dependence on utility grid imports, as seen in Fig. 4.7(b). The port consistently purchases high-cost electricity from the utility grid, particularly during peak demand periods (t9-t15 and t18-t20). This is due to the conventional energy system used in the benchmark model where the port operator mainly relies on obtaining electricity from the national grid to meet overall port demand. Numerical results in Table 4.3 highlight a high operating cost of approximately €3464.248 MWh/day for the benchmark approach, compared to €1571.862 MWh/day with a 54.6% reduction for the proposed system. Shifting from predominantly grid-powered operations to an optimized and self-sufficient microgrid presents the potential for significant daily cost savings. This quantitative analysis highlights the economic advantages of transitioning to an intelligently controlled, modernized localized energy system, revealing the economic infeasibility of conventional systems heavily reliant on the grid.

The reduced purchasing of power from the utility grid in the proposed system in Fig 4.7(b) is explained by the flexible dispatch units in the seaport microgrid as shown in Fig 4.8. The algorithm dispatches renewable generation during peak price periods from t11-t14, supplements with DG units, and battery discharging to avoid costly grid imports.

Any surplus power from PV and WT that is not used for charging the batteries, is sold to the grid, gaining economic benefit for the port operator. In the evening (t18 and t20) as solar fades and wind output is at its lowest level, port operators minimize their costlier grid purchases by discharging the energy from ESS. It also can be observed that the storage control strategy makes use of rate differentials and tries to increase its SOE by charging batteries during low rates at the t1-t6 and t15-t16 time windows. Overall, grid reliance drops 56.5% with energy assets optimally distributed to demands. Simulation validates coordinated scheduling's ability to align supply and loads economically.

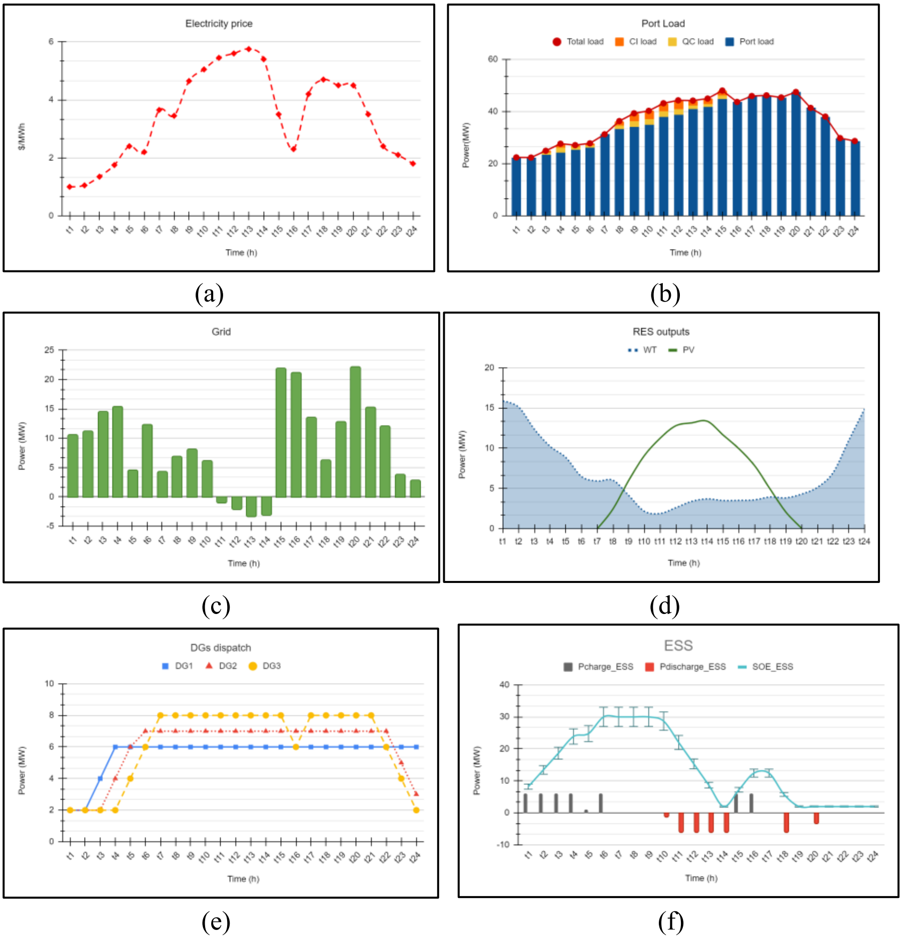


Fig. 4.8. Energy scheduling output of the seaport microgrid.

4.4.2. The Pareto optimal front

Fig. 4.9 illustrates the Pareto optimal front of the bi-objective microgrid optimization in level 2, showcasing the tradeoff between minimizing operating cost and emissions. This non-dominated frontier provides flexibility in decision-making, acknowledging that no single point optimizes both objectives simultaneously. Fig. 4.8(e) details the dispatching pattern of DG units as the cost operation is minimized. To facilitate decision-making, fuzzy set theory is employed, and the circled point on the Pareto curve represents the best compromise option, maximizing minimum satisfaction with a cost of €1670.96 and emissions of 4018.15kg. This graphical representation empowers port managers to align the optimization with their specific goals and constraints.

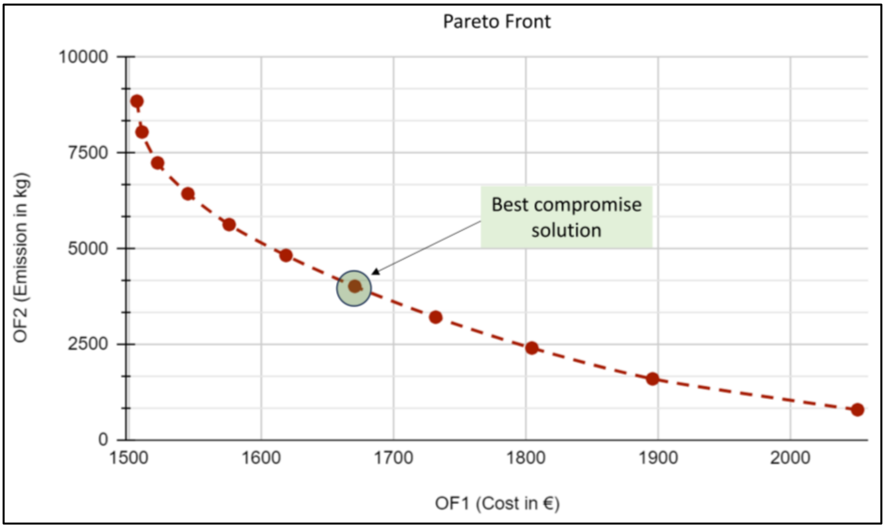


Fig. 4.9. The Pareto optimal front for emission-cost minimization.

4.4.3. Environmental impact

The environmental analysis seeks to assess the impact on emissions reductions through the adoption of integrated cold ironing and localized renewable energy systems in port operations. The assessment considers both shipside and shoreside perspectives, targeting emissions mitigation by eliminating auxiliary engine usage during port stays with the cold ironing while enhancing overall emissions neutrality through localized renewable power of the seaport microgrid. The emissions outcomes from the optimization of seaside operations are presented in Table 4.4.

From the shipside perspective, the proposed model achieves substantial decreases relative to the benchmark model, reducing NO_X by 93.87%, SO_2 by 91.67%, CO_2 by 61.62%, and PM by 83.92%. These remarkable results are the consequence of reducing the whole port stay from 41 to 17 hours and eliminating ships' waiting time. Additionally, the employment of a time-invariant crane assignment strategy in level-one optimization accelerated cargo handling by matching resources to volumes, expediting larger ships. This strategy shows that avoiding unproductive crane movements can decrease berth occupancy. Therefore, the practicality of the proposed scheduling strategies has been demonstrated. Optimized scheduling can reduce waiting and handling times and achieve significant emissions reductions.

Meanwhile, the long port stays under the benchmark model with a total of 41 hours including 4 hours of waiting time is responsible for a significant amount of the pollutant discharge. Ships waiting at anchorage rely on onboard auxiliary engines, emitting higher pollutant levels with the burning MDO fuel. The increased emissions while the ship is at anchor are justified by the higher MDO fuel oil coefficient when compared to the emission coefficient of cold ironing.

Table 4.4. The emissions resulting from the implemented strategy.

Side analysis	Method		NO_X (kg/day)	SO_X (kg/day)	CO_2 (kg/day)	PM (kg/day)
Shipside	Benchmark approach	Diesel	569.9	86.92	28372	15.58
		Cold ironing	126.68	20.4	26906.3	4.54
	Proposed approach	Diesel	236.3	36.04	11764	6.46
		Cold ironing	7.76	1.7	10326.24	0.73
Shoreside	Base system		295.94	64.74	393981	27.75
	Proposed network		68.89	15.07	91709.3	6.458

Nevertheless, when comparing the ship that utilizes cold ironing to the ship with auxiliary engines, both seaside operating scheduling approaches showed a notable decrease in emissions. The NO_X, SO_2, CO_2, and PM were all reduced by 77.77%, 76.53%, 5.17%, and 70.86%, respectively, using the benchmark approach. Reductions were further enhanced to 96.72% for NO_X, 95.28% for SO_2, 12.22% for CO_2, and 88.7% for PM using the integrated optimization approach. This case study highlights the potential for cold ironing to reduce emissions, particularly when combined with coordinated optimization. Optimized scheduling maximizes the potential of cold ironing to reduce ship emissions while in port.

In evaluating the emissions impact from the shoreside perspective, a comparative study is conducted between the conventional grid-dependent base system and the proposed localized microgrid. The base case relies predominantly on carbon-intensive national grid purchases. In contrast, the proposed architecture integrates renewable sources (solar, wind), battery storage, diesel backup, and limited grid transactions, facilitated by the optimization model. The proposed energy configuration with an optimization technique, substantially enhances emission reduction at the port by up to 76.72% for NO_X, SO_2, CO_2, and PM, transitioning from 295.94kg, 64.74kg, 393981kg, 27.75kg to 68.89kg, 15.07kg, 91709.3kg, and 6.458kg, respectively. The degree of emissions reduction is strongly influenced by the composition and proportion of renewable energy sources in the system, with a higher percentage resulting in greater reductions.

The integration of clean energy not only offers ports a dependable alternative energy supply but also contributes significantly to emission neutrality for cold ironing applications. The case study results underline the positive influence of clean energy resources in enhancing the proposed system's capacity to minimize emissions. However, it is important to understand that if the shore's electricity is not obtained from clean sources, cold ironing merely transfers the polluting source from the ships to the shore. In summary, strategic energy diversification, combined with optimization techniques has a promising potential to align port operations with broader decarbonization objectives.

4.5. Summary of the contribution

(1) This research proposed an operation management framework for electrified ports by integrating seaport microgrids and a carbon capture system of cold ironing to reduce fossil fuel dependence.

(2) An energy management system was proposed with a two-level optimization model to synchronize complex operating problems of BAP, CIAP, and QCAP at the seaside with the energy management problem of the seaport microgrid. The integrated approach optimally adopted green technologies to enhance port performance while minimizing operational costs and environmental impacts.

4.6. Conclusion

This chapter demonstrated an integrated optimization paradigm unifying port operations and energy systems. The proposed energy management system with a bilevel optimization framework optimizes berth scheduling, cold ironing, crane assignment, and microgrid control in a coordinated manner, realizing substantial benefits in the handling performance, energy, economic, and environmental benefits. Key conclusions include:

- The developed model provides port operators with an effective port management system to simultaneously optimize electrified operations and sustainable energy supply in support of efficiency and carbon neutrality goals. Non-dominated Pareto solutions empower effective decision-making aligned with strategic priorities.
- Cooperative optimization of operational and energy scheduling unlocks synergistic productivity gains unachievable through benchmark strategies.
- The optimization algorithms have a fast computation time of approximately 2.637 seconds in simulations, demonstrating their feasibility for implementation at ports through automated and computerized control systems coordinating operation resources and energy systems.

This chapter provided quantitative evidence that integrated, optimization-based techniques can play an instrumental role in competitive and responsible port transformations.

Chapter 5. Thesis conclusions

5.1. Research summary

The main goal of this Ph.D. was to minimize emissions from both ships and port activities by incorporating maritime electrification technologies of cold ironing and seaport microgrids. To attain this target, the operation optimization model and energy management system framework were developed to optimally coordinate port operations and energy flows, while maximizing the overall satisfaction of different involved bodies. Based on this directive, studies were conducted, leading to the proposed operation and energy optimization strategies with the following conclusions:

Chapter 1: This research **delivered a comprehensive overview** of port electrification solutions, specifically cold ironing and emerging seaport microgrids, as responses to environmental emissions concerns of the maritime sector. The discussions cover integration barriers, energy prospects, and commonly applied strategies in port management systems, highlighting potential gaps for further investigation.

Chapter 2: A **data-driven approach for forecasting the berthing duration of ships at ports with cold ironing** was proposed. The results indicated that the ANN outperforms other models (MLR, random forest, XG Boost, and decision tree models) with the lowest error deviation, demonstrating its capability to handle nonlinearities in port activity forecasting. It also validated strong correlations between influential factors. The accurate estimation of berthing duration contributes crucial information for port operators about cold ironing power consumption and ship departure time.

Chapter 3: The **seaside port operation optimization model** was designed to manage the complex coordination of BAP, CIAP, and QCAP. The proposed optimization model successfully minimizes ship handling duration by effectively utilizing available port resources and avoiding additional investment costs. The outcome highlighted how crucial it is to minimize ship stay duration to reduce energy consumption, emitted pollution, and operation costs. Besides, the proposed coordination strategy proved valuable for enhancing container port performance, especially when faced with limited resources, offering simplicity and practicality for immediate deployment.

Chapter 4: This research proposed an **integrated energy management system with a cooperative two-level optimization approach** unifying seaside port operations, and seaport microgrid energy management. Quantitative results demonstrated significant reductions in both shipside and shoreside emissions, energy consumption, energy costs, and ships' stay at ports. The proposed solution managed to reassure both port operators and shipping lines by enabling cost savings while guaranteeing compliance with strict regulations, overcoming the conventional paradigm that hinders productivity and sustainability. Thereby, justifying the necessity of incorporating cold ironing into port operations. The Pareto optimal solutions were also provided for maritime stakeholders by presenting a multi-objective decision-making approach. This framework provides methodologies and evidence supporting the instrumental role of integrated optimization in transforming next-generation ports. The work sets the foundation for competitive operations achieving productivity, efficiency, and sustainability through integrated resource coordination and provides a blueprint for responsibly leveraging electrification solutions for the energy transition at ports.

5.2. Contributions

In summary, this research delivers multidimensional applied benefits for researchers, maritime stakeholders, port management, and pathways to achieve decarbonization goals. The contribution of this Ph.D. thesis is breakdown into several standpoints as follows:

1) A comprehensive overview

A comprehensive overview of the port electrification solutions was presented addressing the ports' high-priority concerns, and integration challenges, to uncover research gaps in port operation and energy management systems. Given the maritime industry's urgent need to limit emissions, this overview gives the directive that an electrification solution together with strategic management might assist high performance in port operations to stay competitive while committing to sustainability goals.

2) Developing suitable data-driven forecasting method

The artificial neural network (ANN) model was identified as a model that has high accuracy for predicting the berthing duration of ships at ports with cold ironing, achieving the lowest RMSE of 3.1343 compared to other models. Additionally, the performed correlation analysis provided important insights into relationships between berthing duration and factors like arrival time, ship type/size, operation mode, and capacity index. This aids port operators in understanding behavior related to cold ironing power consumption.

3) Modeling a framework for seaside operation optimization

Modeling of a seaside operation optimization by coordinating different operation scheduling problems involving BAP, CIAP, and QCAP. The formulated optimization model allows ports to maximize the utilization of current assets, which improves operational performance by significantly reducing ships' overall stay duration from 41 to 17 hours, avoiding costly facility upgrades.

4) Developing a two-level seaport microgrid energy management system

Development of a two-level energy management framework that cooperatively synchronizes seaside operation and seaport microgrid energy scheduling. The quantitative analysis obtained from the model simulation shows the improvement in vital maritime aspects of service performance, energy usage, energy cost, and emissions reduction as follows:

- Service performance: A noteworthy 58.54% reduction in ship stay duration at the port, decreasing from 41 to 17 hours.
- Energy usage: Reduction in energy consumption, with a decrease of 52.82% for cold ironing and 31.53% for quay cranes.
- Energy cost: Operating cost of approximately 54.6% has been reduced.
- Emission: Emissions decreased by up to 76.72% for NO_X, SO_2, CO_2, and PM from the shoreside perspective. Meanwhile, shipside emissions were reduced by 93.87% for NOX, 91.67% for SO_2, 61.62% for CO_2, and 83.92% for PM.

5) Contribution to the Green Port Roadmap

- This Ph.D. research work proposes a novel optimization framework that allows ports to adopt clean technologies of cold ironing and seaport microgrids while maintaining their operational efficiency and quality of service.
- The operating costs and obtained emission reduction associated with adopting cold ironing technologies and seaport microgrids give clarity on the benefits that can be gained by port operators and shipping lines which are relevant for decision-making policies.

5.3. Future work

While the port emission concerns from the ship and port sides were addressed by the proposed management system, there are still challenges that require further investigation. Future research directions are detailed as follows:

1) The identified limitation of data-driven forecasting methods in this study is the extensive historical data required. Although larger datasets enable the forecasting to be trained with high accuracy, obtaining a large quantity of data may not always be feasible. Designing limited-data algorithms is important for future work. Possible solutions that need investigation include transfer learning, active learning, and generative models for synthetic data. Enabling accurate forecasting under data scarcity will significantly broaden applicability and unlock the full potential of AI-based methods for maritime systems where data collection is inherently challenging.
2) Testing the optimization system on larger ship volumes is needed to evaluate scalability and robustness for global ports. Systematically increasing ship numbers and types in simulations can reveal performance limits under heavy, diverse traffic. Scalability testing will help validate and generalize the system for multipurpose international ports. Model simplification, decomposition, and distributed computing techniques may be required to enable adoption at higher scales.
3) The optimization framework is currently formulated for seaside operations. Expanding the model's applicability across diverse ports infrastructures, operations, and scenarios will provide insights into applicability across different contexts. Future studies might improve the system by incorporating larger-scale logistics management encompassing landside operations like yard and gate scheduling.

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Part II

Papers

Paper I

Electrification Of Onshore Power Systems In Maritime Transportation Towards Decarbonization Of Ports: A Review Of The Cold Ironing Technology

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Data-Driven Ship Berthing Forecasting For Cold Ironing In Maritime Transportation

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Paper III

A Review Of The Conceptualization And Operational Management Of Seaport Microgrids On The Shore And Seaside

Nur Najihah Abu Bakar, Josep M. Guerrero, Juan C. Vasquez, Najmeh Bazmohammadi, Yun Yu, Abdullah Abusorrah, Yusuf A. Al-Turki

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Paper IV

Optimal Configuration And Sizing Of Seaport Microgrids Including Renewable Energy And Cold Ironing – The Port Of Aalborg Case Study

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Environmental Dispatch Strategies For Onshore Power Systems

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Paper VI

Optimal Berth Allocation In Ports With The Deployment Of Shore To Ship Power System

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