Collaboration for Resilient and Decarbonized Maritime and Port Operations

Lyu, X.

DOI
10.4233/uuid:fbf197e1-aba4-4686-80bb-e840707aee1a

Publication date
2024

Document Version
Final published version

Citation (APA)
Lyu, X. (2024). *Collaboration for Resilient and Decarbonized Maritime and Port Operations*. [Dissertation (TU Delft), Delft University of Technology]. TRAIL Research School. https://doi.org/10.4233/uuid:fbf197e1-aba4-4686-80bb-e840707aee1a

Collaboration for Resilient and Decarbonized Maritime and Port Operations

Lyu, X.

Publication date
2024

Document Version
Final published version

Citation (APA)
Lyu, X. (2024). *Collaboration for Resilient and Decarbonized Maritime and Port Operations*. [Dissertation (TU Delft), Delft University of Technology].

Collaboration for Resilient and Decarbonized Maritime and Port Operations

Xiaohuan LYU

Collaboration for Resilient and Decarbonized Maritime and Port Operations

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof.dr.ir. T.H.J.J. van den Hagen,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op donderdag 21 november 2024 om 10:00 uur
door

Xiaohuan LYU
Master of Engineering in Transportation Engineering,
Shanghai Jiao Tong University, Shanghai, China
geboren te Yantai, China.

Dit proefschrift is goedgekeurd door de promotoren:
Prof.dr. R.R. Negenborn
Dr. F. Schulte

Samenstelling promotiecommissie:

Rector Magnificus	voorzitter
Prof.dr. R.R. Negenborn	Technische Universiteit Delft, promotor
Dr. F. Schulte	Technische Universiteit Delft, copromotor

Onafhankelijke leden:

Prof.dr. ir. K.I. Aardal	Technische Universiteit Delft
Prof.dr. C. Cleophas	Kiel University
Dr. R.G. González Ramírez	Universidad de los Andes
Dr. ir. E.A. Lalla-Ruiz	University of Twente
Prof.dr.ir. L.A. Tavasszy	Technische Universiteit Delft

The research described in this thesis was supported by the China Scholarship Council under grant 202107720039.

TRAIL Thesis Series T2024/14, The Netherlands TRAIL Research School

Published and distributed by: Xiaohuan LYU
Cover design: X. Lyu and N. Kougiatsos
E-mail: summerlv@alumni.sjtu.edu.cn

ISBN 978-90-5584-353-4

Keywords: Collaboration, Maritime and port operations, Operation Research, Cooperative game theory.

Printed in The Netherlands

“Go left when nothing goes right”

Preface

When the moment came, I felt more emotions after going through initial periods of enthusiasm for pursuing a PhD and middle periods of self-doubting.

First and foremost, I would like to express my sincere gratitude to my supervision team. Rudy R. Negenborn, thank you for your guidance and support as my promoter during my PhD. Your wide insights, quick mind, and well-organized working style always impress me. I appreciate your open door to me whenever I get stuck, which is very supportive. Frederik Schulte, my co-promoter, I am grateful for your assistance when I applied for the PhD position at TU Delft. In addition, I would like to say a big thank you to Jiangang Jin, my Master's supervisor. Your academic taste and intuition greatly inspired me. Without you, I would never have started my PhD journey.

I would also like to express my sincere gratitude to my friends, colleagues and those who are both friends and colleagues. I am so lucky to meet all of you in the Netherlands, and those shining memories will always be in my mind. Thanks to all the colleagues in the MTT department, working in this lovely group is enjoyable. Special thanks to the Whatsapp groups for the unforgettable memories—road trip to the Atlantic, sunset singing, homemade meals, board games, office gatherings, the Swiss game, and birthday celebrations. I believe our friendship will endure despite the physical distance after graduation. I also extend my gratitude to my friends in the WeChat group. I cherish our shared experiences—broadcast recording, gossiping hours, cocktails night, blue waves on the beach, extra working and struggling in the library and Echo, fireworks in the new year, night walking with casual and in-depth discussion, and countless companionship. Then, it is so lucky to meet those amazing girls from all over the world, and I look forward to having more fun with you in China in the future. Finally, to TJ, my boyfriend, thank you for listening to my complaint patiently especially when I am depressed. Additionally, thanks to my remote friends on other continents, you have provided me with immense support through inspiring conversations.

Finally, I am profoundly grateful to my family. My mother, with her strong inner beliefs, and my father, with his immense patience, have been significant influences on my personality. Your unconditional love and support have been my foundation. You are the best parents, teachers, and friends of mine.

Xiaohuan Lyu,
Delft, June 2024

Contents

Chapter 1

Introduction

Maritime shipping plays a vital role in global trade, calling for the harmonized engagement of diverse stakeholders, including shipping lines, ports, and multiple logistics service providers. Fostering collaboration among these stakeholders remains essential for enhancing operational efficiency, particularly amid the imperatives of bolstering resilience underscored by the COVID-19 pandemic and achieving net-zero emissions by 2050. Although collaborative strategies in maritime transport have been suggested for decades, the research is still in its infancy stage of conceptual demonstration and needs more support for real-world operations. At the same time, technological advancements provide new opportunities for advanced collaboration, but new challenges also come along with them. This thesis presents a multifaceted exploration of novel collaborative paradigms within maritime and port operations, and it focuses on contributions based on Operations Research (OR) methodologies. This thesis elucidates how collaborative frameworks can drive advancements in maritime transport, facilitating efficiency gains, resilience enhancement, and progress towards a decarbonized, emissions-neutral future.

This chapter sets the scope and dimensions of collaborative maritime and port operations discussed in this thesis, introduces the challenges and describes the solutions we propose. First, Section 1.1 provides the research background. Then, Section 1.2 introduces the scope and describes the research motivation. Next, Section 1.3 details our research questions, and Section 1.4 presents the contributions of this thesis. Finally, the outline of this thesis is given in Section 1.5.

1.1 Background

Maritime transport is a critical component of global supply chains and the world economy, responsible for more than 80% of worldwide trade and exhibiting a rising trend, even though there was a 3.8% reduction in 2020 because of the COVID-19 pandemic [1]. The United Nations Conference on Trade and Development (UNCTAD) states that total seaborne trade has increased by 2.4% in 2023 and will continue growing for the medium term (2024-2028) [2]. Indeed, it is conceivable that the maritime shipping sector is shifting towards the dominance of mega-ships and ports, with carriers and ports striving to optimize transportation capacities.

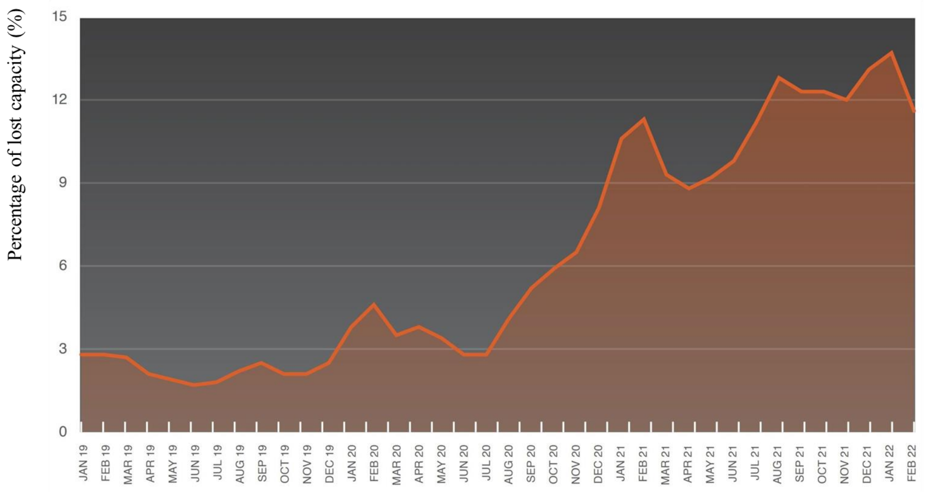


Figure 1.1: Global container fleet capacity lost to congestion [3]

Over the past few years, the maritime shipping industry has struggled with the challenge of coping with escalating volumes, resulting in prolonged periods for vessels awaiting loading and unloading at ports. This phenomenon has led to a significant increase in global shipping capacity lost to congestion, as illustrated in Figure 1.1, with the average reaching 11.1% in 2021, a stark rise from 2.3% in 2019, deteriorated by the impact of the COVID-19 pandemic. Data from the start of 2022 indicates a continued upward trend, indicating substantial disruption to the global supply chain. This underscores the need for efforts and advancements in efficiency and resilience enhancement within maritime shipping.

Figure 1.2 shows the total carbon dioxide emissions in international shipping over the past decade, depicting a persistent upward trend. As reported by [2], maritime transport is responsible for 2.8% of all greenhouse gas (GHG) emissions. To achieve the goals outlined in the Paris Agreement [4], particularly the pursuit of limiting temperature rise to 1.5°C above pre-industrial levels, calling for urgent action to meet decarbonization and net-zero targets set forth by the International Maritime Organization (IMO), as emphasized in [2]. In essence, maritime transport finds itself at the forefront of a transition towards a future characterized by enhanced efficiency, resilience, and decarbonization. This necessitates the implementation of innovative measures.

Over the last decade, collaborative transport platforms like Uber (Freight), Lyft, Cargonexx, Blackbuck, and Quicargo have begun to disrupt the mobility and freight transportation industry. A general concept of collaboration is “an intentional property that derives from the shared belief that together the network members can achieve goals that would not be possible or would have a higher cost if attempted by them individually” [5]. In the transportation domain, collaboration among multiple stakeholders facilitates the sharing and coordinating of resources, including vehicles, facilities, and transport requests. In fact, collaboration has been applied in maritime transport for decades [6], such as in the form of shipping pools and shipping alliances.

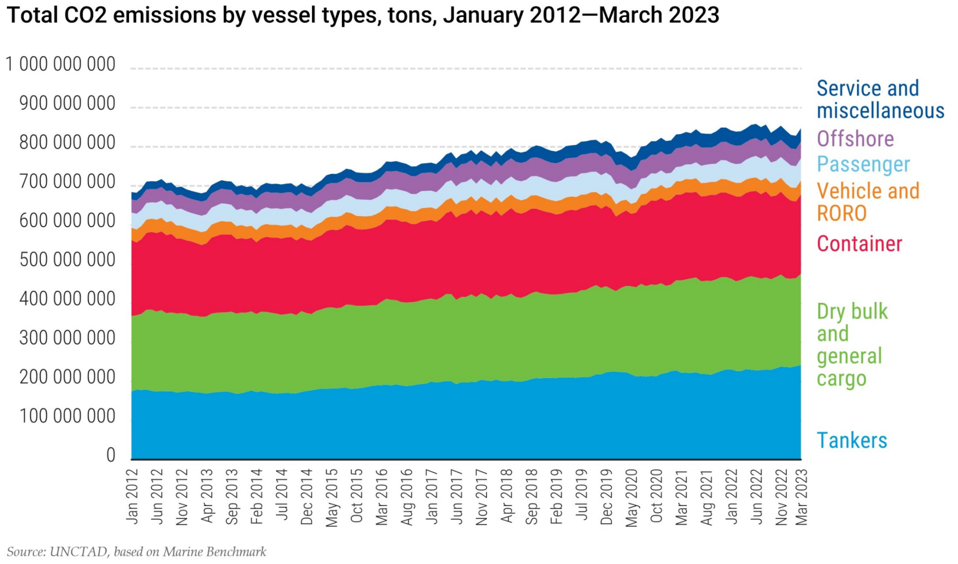


Figure 1.2: Total carbon dioxide emissions by different vessel types [2]

Table 1.1 summarizes recent maritime projects implemented in practice using the framework of collaborative platforms, presenting their names, users, functions, current status, and open issues towards more practical trends. Port Community System (PCS) is an electronic platform that integrates various subsystems, facilitating information exchange among stakeholders [7], which enables improved coordination of vessel arrivals and port operations, such as *Portbase* and *OnePort*. To reduce GHG emissions, company NAPA provides a *Blue Visby* platform to approach the ”Just-in-Time” goal. In recent years, IoT and blockchain have been integrated with PCSs to address the bill of lading issues, indicating the trends from PCS towards Physical Internet (PI), such as *NxtPort*, *NextLogic*, *Nexus*, *C-port prototype*, and *SmartPORT*. Other platforms are based on the sharing economy in the liner shipping market. *CargoStream*, a centralized collaboration platform for the port supply chain, is developed to aggregate the needs of shippers and optimize shipping options for specific cargo. *Avantida* and *EuroTransCon* support reusing empty containers from import operations to export operations. Maersk is deploying a spot booking platform, *FreightHub*, which is regarded as an effort to improve freight forwarders' functionality by offering shippers dynamic prices and guaranteed container slots. Similarly, *Xchange* and *iContainers* carry out container exchanges to improve collaboration and simplify the global container trade. *E-shipping Gateway* and *Landstar*, as port-associated truck service platforms, attempt to offer information on haulage demand directly to truck drivers via smartphone applications.

However, as shown in Table 1.1, there are still open issues relevant to information sharing, business frames, operational details (bundling and synchronizing), regulatory issues, and technological support. Therefore, in response to the strong demand for extensive collaboration within the maritime transport sector and the potential trends toward practical implementation, academia is tasked with directing its attention to the exploration of novel, supportive, and promising collaborative strategies.

Table 1.1: Practical implementations of collaboration in maritime and port operations

Name	User	Function	Status			Open issues
			R	P	C	
Portbase	Port of Rotterdam	Data sharing for more efficient port cargo flows	✓			Port as information centers
OnePort	Port of Hong Kong	Data sharing for port logistics streamline	✓			Port as information centers
Blue Visby	General product	Vessel arrival optimization		✓		Information sharing frame
IoT-blockchain PCS	General product	Bill of lading optimization			✓	Business frame design
NxtPort	Port of Antwerp	Data sharing for port efficiency	✓			Regulatory issues
NextLogic	Port of Rotterdam	Port supply chain collaboration	✓			Intermodality vs. multimodality
C-port PCS	Port of Livorno	Port supply chain collaboration			✓	Port as information centers
SmartPORT	Port of Hamburg	Port logistics streamline	✓			Bundling and synchronizing flows
CargoStream	General product	Port supply chain collaboration	✓			Bundling and synchronizing flows
Avantida, EuroTransCon	General product	Empty container reuse	✓			Environmental issues vs. cost-based concerns
FreightHub	Maersk	Container sharing	✓			Bundling and synchronizing flows
Xchange, iContainers	General product	Container sharing	✓			Bundling and synchronizing flows
E-shipping Gateway, Landstar	General product	Port-associated truck haulage	✓			New technologies application

Note:Status: R: realized; P: prototyped; C: concepted

1.2 Research scope and motivation

Technological advancements in recent years, such as the Internet of Things (IoT), 5G networks, big data and Blockchain, have created new opportunities for conventional forms of collaboration and promoted the innovation of collaborative business frameworks in the transportation area. Early efforts in collaborative maritime transport were primarily directed at enhancing the competitiveness of participants [6], with subsequent emphasis shifting towards environmental sustainability and resilience objectives. Given the multifaceted nature of stakeholders directly and indirectly engaged in maritime transport, our focus is collaboration within the realms of ocean shipping, port operations, and port drayage (from depot to terminal). Notably, collaborative strategies for inland waterways have been dedicatedly discussed in [8, 9]. Thus, inland cargo transportation is outside the scope of our collaborative maritime and port operations discussed in this thesis.

Figure 1.3 conceptualizes the collaborative maritime and port operations discussed in this thesis, which is scoped by the following dimensions:

Collaboration Types: We categorize the collaboration type based on the relative position of participating partners. Following [5], this dimension has mainly considered two categories: vertical and horizontal. In vertical collaboration, players fulfilling different transportation parts are now coordinated to synchronize the flow of goods to enhance efficiency, such as integrating port operations with ship schedules [10]. In contrast, horizontal collaboration involves participants at the same level of the transportation supply chain who aim to maximize resource utilization by sharing capabilities and exchanging information [11]. This type often means pooling resources and information, necessitating strong incentives to encourage individual partners to collaborate. Planning challenges in horizontal collaboration in transportation are frequently related to shared vehicle routing, cost and profit distribution, and coalition stability.

Involved Stakeholders: Three primary stakeholders are considered to be involved in collaboratively organizing maritime transport activities: shipping lines, port or terminal operators, and other transport or logistics service providers. We use different stakeholders involved to differentiate collaborative relationships and planning models. Shipping lines are responsible for operating ships transporting cargo across the sea, while ports or terminals offer loading and unloading services to incoming ships. In this research, decision-makers who provide berths and (un)loading services for the calling vessels are referred to as terminal operators, and those who arrange vessel services before (un)loading vessels at the designated berth are called port operators. Generally, several terminals are within one port, and if a central authority organizes their operation, terminal operators can also be referred to as port operators. In most cases, the term ‘terminal operators’ depicts the stakeholders responsible for orchestrating ship-port calling operations within this research. Distinctions between port operators and terminal operators will be explicitly elucidated when necessary. Additionally, other container drayage service providers (e.g., trucks, rails, and barges) play a crucial role in connecting port or terminal operations with ocean shipping, and these decision-makers are also included in the scope.

Objectives: Collaboration has held great promise in achieving the following ambitious goals in maritime transport. The basic is efficiency improvement. Some existing works focus on evaluating the impact of collaborative planning on the profit of both individuals and the community [12, 13], which confirms that collaboration in freight transportation has the potential to improve market share and enhance profitability. Then, it is resilience. Collaborative activities increase the system resilience via increased visibility, flexibility, and responsiveness [14, 15]. Following the overarching idea that collaboration makes the coalition and the individual more profitable, more ecological, and less vulnerable to disruptive events, allowing them to recover easier and faster, the maritime industry can benefit in numerous ways from developing collaborative transportation systems. The last is decarbonization towards a zero-emission future. Whereas decarbonization in transportation remains challenging, there is excellent potential through shared infrastructure based on application and further development of Artificial Intelligence (AI), Simulation, and OR [16].

Over the past decades, many research efforts have highlighted the significant benefits of collaboration for maritime transportation chains [17]. Recently, a collaborative port logistics system framework has been proposed in [18], providing a reference for port supply chain integration and collaboration.

However, even though collaboration holds great promise in maritime and port operations, studies that can support operational practices are still limited, scattered, and fragmented [19]. Past experiences have shown the challenging nature of this approach, as these collaborative strategies with new features require additional efforts in collaborative planning models to guide their effective implementation. Given the recent developments in the collaboration of road transportation [10], it is timely to look at how the corresponding academic research is evolving in the maritime sector. This thesis classifies dimensions and sheds light on OR methods for collaborative maritime and port operations. Significantly, the thesis clarifies how collaboration in maritime transport resembles or needs to be distinguished from problems in other domains of collaborative transportation. When implementing collaborative models, it is important to consider the multi-sided interest setting because of the multiple stakeholders involved, where it is crucial to design clear incentives to motivate potential partners to engage in an ad-hoc kind of collaboration. Consequently, collaboration incentives should become an integral part of decision support models, and they need to be developed on an operational planning level and applied dynamically.

The main research gaps for collaboration towards efficient, resilient and decarbonized maritime transport are identified in Chapter 2, generally with two aspects: novel business models based on the concept of collaboration and the corresponding development of planning models to facilitate practical implementation. The dimensions of collaboration type, involved stakeholders, and objectives outlined above serve as clues for reviewing existing literature, with specific research gaps detailed in Chapter 2.

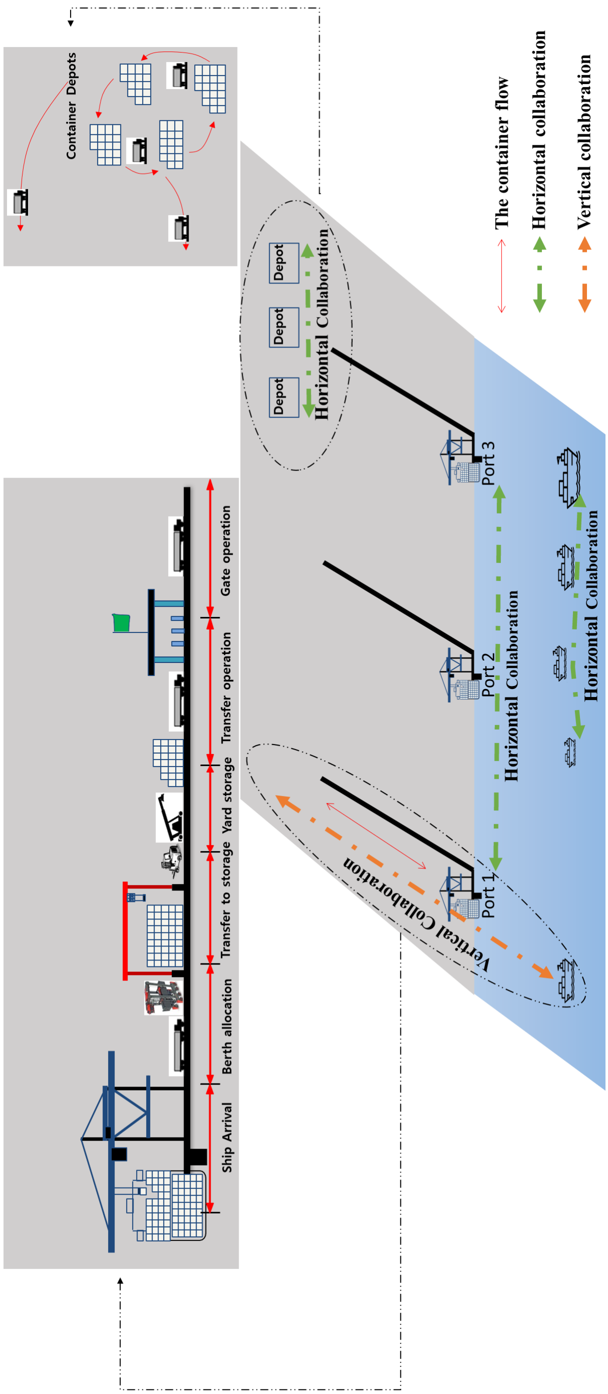


Figure 1.3: Scope of collaborative maritime and port operations in this thesis

1.3 Research questions

The main research question of this thesis is:

How can collaborative strategies contribute to maritime and port operations towards a higher level of efficiency, resilience, and decarbonization?

To answer the above question, the following sub-questions are addressed:

Q1: *What are the characteristics and key challenges of collaborative maritime and port operations?*

Although the innovative research of collaborative systems with new objectives dedicated to maritime transport just started in recent years, classical collaboration in maritime shipping has been suggested and studied for many years.

In this thesis, we answer this question with a comprehensive survey in Chapter 2. To address this question, this survey will begin by identifying and classifying the inherent characteristics of collaborative maritime and port operations through an in-depth literature review.

Q2: *How do OR methodologies contribute to the decision-making of collaborative systems in maritime and port operations?*

Regarding decision-making, OR has provided significant support for collaborative transportation [20, 21]. More comprehensively and concretely, the survey of [10] focuses OR contributions on urban freight transportation, including the shared costs (or profits) allocation for incentivizing collaboration. However, a dedicated literature survey on collaborative maritime and port operations from the OR perspective is nonexistent.

In this thesis, we answer this question with a comprehensive survey in Chapter 2. To address this question, in the survey, we specifically group the optimization problems in terms of vertical and horizontal collaboration, summarizing the OR contributions (e.g., innovative models, algorithms, and mechanisms) in dealing with each type of collaborative optimization problem.

Q3: *How does collaboration work as a means for efficient and resilient port operations?*

Insufficient information sharing and coordination within maritime and port operations systems has resulted in significant financial losses and cascading adverse effects in maritime transport. Moreover, recent supply chain disruptions and crisis responses (e.g., the COVID-19 pandemic and the Red Sea crisis) have highlighted the importance of resilience. Thus, there is a growing recognition within the maritime industry of the necessity for advanced collaboration among diverse stakeholders to elevate efficiency and resilience.

To answer this question, we examine two types of collaboration — horizontal in Chapter 3 and vertical in Chapter 4 — to develop proficient collaborative planning frameworks and demonstrate the resulting enhancements in efficiency or resilience. In Chapter 3, we will explore a collaborative berth allocation problem for container terminals based on the collaboration of terminal operators. In Chapter 4, we study an integrated berthing planning problem for bulk terminals considering the unavailability and stock level constraints, which cooperatively outputs a joint decision on both berth allocation and inventory management.

Q4: *How to generate attractive and stable collaboration?*

Real-world collaboration in maritime transport is operated with the involvement of multiple stakeholders, inevitably involving a trade-off of the interests among participants. Besides, players may not be willing to share all the information due to competition or fraud to manipulate the game. In this regard, it is crucial to design attractive incentives to motivate individual stakeholders to engage in and enable stable collaboration.

To answer this question, we design a scheme for incentive cost allocations in the collaborative game in Chapter 5. In detail, we propose a cooperative berth allocation game based on the horizontally collaborative berth allocation problem. Then, we develop the core and the nucleolus for cost allocations based on cooperative game theory. Finally, we plan to propose the algorithms that provide solutions for the core and the nucleolus. Following the above steps, we aim to formulate a general-purpose method to obtain cost allocations (the core and the nucleolus) to establish a stable collaboration.

Q5: *How to design green maritime corridors for achieving a decarbonized or zero-emission future in maritime shipping?*

The maritime shipping industry is facing increasing pressure to decarbonize and ultimately zero emission due to the escalating threats of climate change. This urgent need has inspired the conceptualization of green maritime corridors—a designated network of shipping routes, ports, and associated infrastructure designed to advocate shipping practices with low or zero emission. However, establishing green maritime corridors is still in a conceptual state, and studies from the implementational perspective are still lacking.

To answer this question, we propose a new mathematical model for the corridor network design and refueling station location problem in Chapter 6.

1.4 Contributions

The contributions of this thesis are summarized as follows:

(1) A comprehensive review of prior research and practical applications concerning collaborative strategies in maritime transport, taking a critical look at the challenges and how OR methodologies contribute. These collaborative systems inherently open up new spaces for decision-making optimization while simultaneously introducing novel OR challenges, thereby necessitating the development of innovative models to support system functionality. This research improves the understanding of collaborative concepts for maritime researchers and practitioners, and research gaps and agendas are also identified to catalyze future OR research on innovative collaboration frameworks [19].

(2) Establishing mathematical OR models for collaborative systems dedicated to different areas of maritime and port operations to achieve higher efficiency, resilience, and decarbonization towards zero emission [22–24]. Particularly, to achieve net-zero targets in the future, we provide a first optimization approach for designing green maritime corridors, guiding policymakers and industry players on the way to successful implementations [24].

(3) Designing attractive and stable allocation schemes for coalitional costs (or profits). Based on cooperative game theory, the allocation mechanisms are proposed to make it clear to individual stakeholders how much they stand to gain to avoid some players benefiting greatly while some even not, thereby maintaining a stable collaboration. The proposed mechanism design algorithms for collaboration stability provide general-purpose approaches to achieve attractive and stable cost (or profits) allocations for collaborative combinatorial optimization problems [25].

1.5 Thesis outline

The outline of this thesis is shown in Figure 1.4.

- Chapter 1 introduces the research subject.
- Chapter 2 addresses research question **Q1** and **Q2**, comprehensively reviewing the collaborative approaches in maritime and port operations studies.
- Chapter 3 addresses research question **Q3**, investigating a horizontal collaboration approach based on terminal consolidation for more efficient and resilient port operations.
- Chapter 4 addresses research question **Q3**, exploring a vertical collaboration approach based on integrating multiple considerations from stakeholders at different levels from the supply chain perspective for enhancing port operations.
- Chapter 5 addresses research question **Q4**, aiming to design attractive cost allocation mechanisms to maintain a stable collaboration and provide a general method for collaborative forms in both maritime shipping and port operations.
- Chapter 6 addresses research question **Q5**, defining the corridor network design and refueling station location problem, supporting green maritime corridor design for decarbonization even zero-emission goals in maritime shipping.
- Chapter 7 concludes the thesis and provides further research directions.

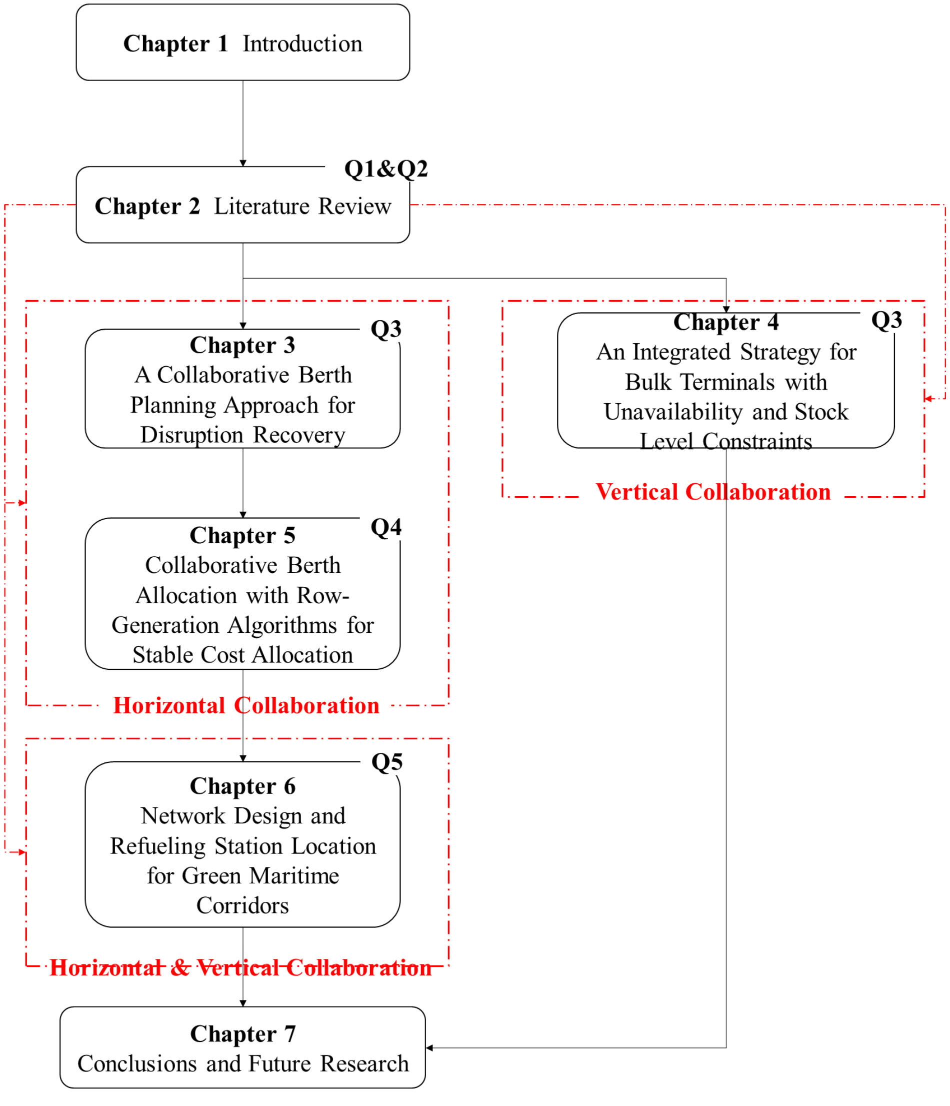


Figure 1.4: The outline of this thesis.

Chapter 2

Literature Review of Collaborative Maritime and Port Operations

The research topic of this thesis is collaboration towards resilience and decarbonization for maritime and port operations. In recent years, more research efforts have underscored the significant benefits of collaboration within maritime transportation chains. To better understand this topic and identify research gaps, we conduct a comprehensive survey in this chapter that overviews collaborative approaches in the prior research within the maritime transport sector and discusses the challenges these collaborative systems face. With that, this chapter addresses research questions: **Q1**: "What are the characteristics and key challenges of collaborative maritime and port operations?" and **Q2**: "How do OR methodologies contribute to the decision-making of collaborative systems in maritime and port operations?"

There are primarily two types of collaboration: vertical and horizontal. In vertical collaboration, participants come from different levels from the perspective of supply chains. The key is synchronizing transport activities at different levels and letting them function as an integral system. For horizontal collaboration, the focus transforms to cooperating with different players at the same level to achieve economies of scale. Consistent with this category, the remainder of this chapter is organized as follows.Section 2.1 describes the search strategy for collecting the research papers. Section 2.2 details vertical types of collaborative maritime and port operations, and Section 2.3 addresses horizontal types. Section 2.4 concludes the chapter and emphasizes the key research gaps.

This chapter has been submitted to a journal. [1].

2.1 Searching method

We collect the references in three stages to obtain the relevant literature:

[1] X. Lyu, K. Tierney, F. Schulte (2024), Collaborative maritime and port operations: A literature review and roadmap.

(1) We search keywords including "maritime shipping" and "collaboration" in the Scopus database. We also consider the keywords' synonyms as replacements, such as "collaborative", "cooperation," "cooperative," "synchronization", or "sharing" to substitute the concept of collaboration. Initially, 568 research papers were included, and then by limiting the database to the English language and peer-reviewed articles, 299 results were obtained.

(2) Since we mainly concentrate on the OR methods in collaborative maritime and port transportation, the corpus of literature is further refined by checking the title and abstract.

(3) We complement the list by looking through references that they cite or by which they are cited, with 237 publications in total.

2.2 Vertical collaboration

Maritime transportation relies on a complex chain of interconnected operations, including sailing between two ports (legs), vessel calls at specific ports, and cargo logistics and operations within each port. In practice, different stakeholders are involved and organize their activities independently. This operational independence can lead to inefficiencies from the supply chain perspective, aggravated by increasing environmental and resilience concerns. To address these challenges, vertical collaboration, where multiple stakeholders at different decision-making levels organize their operations cooperatively, has emerged as a promising solution. However, implementing vertical collaboration in the complex and large-scale maritime shipping industry takes time and effort. In this section, we aim to answer the following questions by conducting the literature survey: (i) What forms of vertical collaboration are possible among stakeholders in maritime shipping? (ii) What are the potential positive impacts of such collaboration on efficiency, decarbonization, and resilience? (iii) What significant decision-making challenges do stakeholders face in each form of collaboration, and how can they be addressed?

We divide activities in maritime shipping into the inter-port and intra-port processes. Inter-port operations consist of port call procedures involving sailing legs, vessel calls, and (un)loading vessels at terminals among different ports, which involves cargo flows among multiple ports. In contrast, intra-port operations refer to multiple logistics activities to move cargo flows happened at a single port. Given this context, we categorize vertical collaboration into inter-port collaboration for vessel services (Section 2.2.1) and intra-port collaboration for cargo services (Section 2.2.2). An overview of related research papers organized according to the above categorization is provided in Table 2.1, providing decision problems for each category, special considerations, and the involved stakeholders correspondingly.

2.2.1 Inter-port collaboration for vessel services

In inter-port collaboration, we identify three main stakeholders for vessel services. The first is the shipping line, also known as ocean carrier, which specializes in transporting containerized goods via scheduled vessels along predetermined routes. The second is the terminal operator providing berths and (un)loading services for the calling vessels. The third is the decision-maker that arranges different vessel services (e.g., towage by tugboat or mooring by boatmen) before (un)loading vessels at the designated berth, referred to as port operator due to the services are provided when the vessel is approaching terminals after arriving at the port.

Figure 2.1 depicts the vessel services process at the port and outlines the inter-port collaboration for vessel services, discussed in vessel calling optimization and vessel berthing optimization, respectively. Decisions regarding vessel services by various stakeholders are intricately interconnected. For instance, departure times at each port heavily depend on the handling rates provided by terminal operators, which directly influence subsequent legs and port calls. However, real-world scenarios are inherently non-deterministic, with disruptions occurring frequently. For instance, vessel delays due to port congestion can result in extended waiting times for towage services. Such delays at one port can propagate along the routes, leading to unnecessary losses and inefficiencies. Therefore, synchronizing decision-making processes through effective collaboration holds promise for enhancing overall performance.

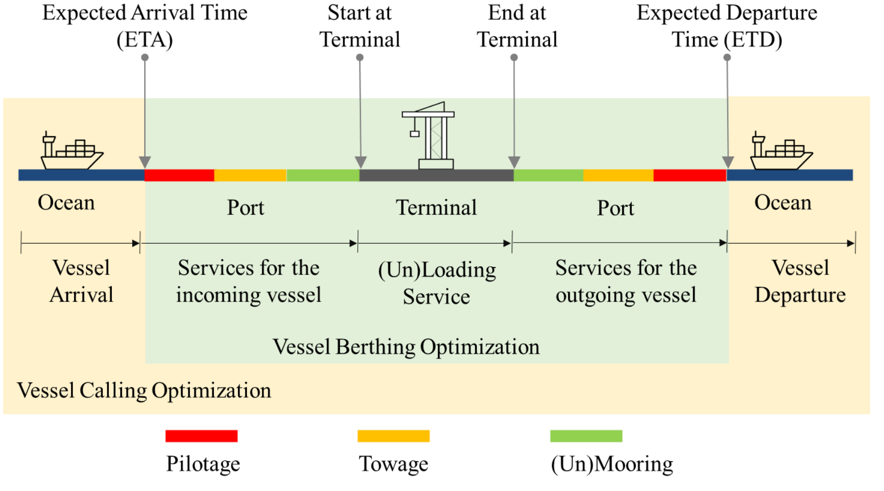


Figure 2.1: Inter-port collaboration for vessel services.

Table 2.1: An overview of vertical collaboration in maritime and port operations

Category	Decision problem	Special consideration	Involved stakeholders SL	TO	PO	LP	References
Inter-port collaboration for vessel services	Vessel calling optimization	Speed optimization	✓	✓	✓		[26] [27]
		Flexible calling terminals	✓	✓	✓		[28] [29]
		Flexible handling rates	✓	✓	✓		[30] [31]
		Collaborative vessel scheduling	✓	✓	✓		[32] [33]
	Vessel berthing optimization	Pre-berthing services		✓	✓		[34] [35] [36]
		Berth allocation	✓	✓	✓		[37] [38] [31]
		Container Stowage	✓	✓	✓		[39] [40]
Intra-port collaboration for cargo services	Coordination of multiple transport processes	Integrated planning				✓	[41] [42] [43] [44]
		Innovative system				✓	[45] [46] [47] [48] [49]
	Synchronization of Inter-terminal Transport (ITT)	Sea-rail transportation		✓		✓	[50] [51]
		Sea-barge transportation		✓		✓	[52]
		Integrating ITT with handling operation	✓	✓	✓	✓	[53]
	Truck Appointment System (TAS)	TAS for port gate control		✓	✓	✓	[54] [55] [56]
		TAS for container empty mangement		✓	✓	✓	[57] [58] [59]
Intra-port collaboration for both vessel and cargo services	**Vessel berthing optimization**	**Berth allocation**	✓	✓		✓	**This thesis**

Note: SL: shipping lines; TO: terminal operators; PO: port operators; LP: logistics service providers

Vessel calling optimization

Vessel calling optimization is of great significance for reducing the vessels' unproductive waiting time at ports and terminals. Numerous studies integrate port availability factors (e.g., occupancy, weather, and tidal) into vessel scheduling to approach the case of Just-In-Time (JIT) operation for calling vessels at the port. More recent research focuses on flexible voyage speeds by considering the calling terminals' operating situations such as buffer times and available time windows [27]. In [26], the voyage speed is optimized according to the port capacity by synchronizing arrival times for all vessels heading to the same port. A Blue Visby Solution (BVS) is proposed to dynamically adjust vessel sailing speeds while ensuring a predetermined service rate at the port and maintaining the vessels' designated arrival order.

Collaboration makes decisions bilateral. Some studies work on novel collaborative agreements wherein shipping lines are empowered to select the calling terminals or the handling rates at the terminal according to specific criteria negotiated with terminal operators. In [28] and [29], novel collaborative agreements are introduced wherein shipping lines are empowered to select the calling terminals for each port of call according to their specific criteria, including preferred time windows and handling rates. A bi-objective optimization model is formulated to balance costs and emissions satisfactorily. Furthermore, the authors make a valuable contribution by proposing an exact algorithm for solving such multi-objective optimization problems instead of relying on meta-heuristics. Traditionally, the handling rates are unilaterally decided by port or terminal operators, while the collaboration makes it bilateral. In [30], a mechanism is designed for the shipping line to choose whether to pay additional fees for a higher handling rate. The experimental results of [30] show that the proposed mechanism leads to considerable fuel savings for shipping lines with a slight increase in service fees paid to the port, and [31] also consider similar compensation but from the perspective of the utility estimation provided by both shipping lines and terminal operators.

On top of variable voyage speed and interactive terminal handling decisions, some studies focus on integrated operational decisions with vessel scheduling in the collaborative setting with port operators. In [33], the authors aim to minimize the total bunker consumption of the shipping network by optimizing the schedule of port call times. To control the extent of slow steaming and avoid administrative troubles for ports, the authors limited the number of port visits that could be rescheduled and introduced penalties for such modifications. In [32], container allocation is considered cooperatively on legs when making vessel schedules for the shipping lines, which incorporates both the container shipping and demurrage costs incurred due to waiting at the port.

Vessel berthing optimization

Various services, including pilotage, towage, and mooring, are provided by different stakeholders. Such services berthing at one terminal and must be readily available once a vessel arrives at the port. These pre-services are also involved in the vessel berthing process, and inefficient service connections between them can cause extra waiting time and correspondingly increase vessel turnaround time at the port. Since [60] stated that a cooperative port service system is more effective than non-cooperative cases, more recent studies have started looking at organizing pre-services cooperatively by modeling information exchange between service-provider departments [34], integrated pilotage and tugging operations planning [35], and joint decision-making among shipping lines and multiple port pre-service departments [36]. In [34], the information exchange between the port's pilotage and towage service departments is modeled to the case of the Port of Rotterdam, leading to waiting time savings of up to 30%. In [35], pilotage and tugging operations are considered simultaneously to schedule vessel movements within the port before berthing operations. An exact algorithm based on constraint separation is presented to solve the proposed MIP model to minimize vessel waiting time at the port. In [36], a collaborative planning model of loading operation planning and channel traffic scheduling is proposed for dry bulk export ports.

The Berth Allocation Problem (BAP) is one of the most critical problems for terminal operators, involving deciding on when and where to (un) load the vessels. The solution of the BAP can influence the shipping lines' voyage indirectly. Many studies examine the collaborative BAP with the involvement of shipping lines. In most academic research on berth allocation, the vessels' arrival time is often regarded as a fixed parameter, while it can be varing in the collaborative setting [37]. Then, an enhanced BAP model is proposed by allowing terminal operators to offer calling time windows to shipping lines [31, 38].

Inefficient yard container staking can result in significant container rehandling operations, leading to increased costs for container terminals and longer turnaround times for shipping lines. Thus, terminal operators need to coordinate yard container stacking for berthing optimization [39, 40]. In [39], an Integer Linear Program (ILP) model is proposed to minimize the relocations in the terminal yard. The study also considers the quay-side shifts of containers generated in the subsequent ports in the vessel stowage plan. Similarly, the authors of [40] define a Flexible Ship Loading Problem (FSLP) in which the terminal operator has the authority to select the container to be loaded in each slot according to a roughly class-based stowage plan provided by the shipping line.

2.2.2 Intra-port collaboration for cargo services

The cargo movement within a port involves various transport operations after or before the cargo is loaded into (or unloaded from) vessels, leading to ITT. This section focuses on studies related to vertical collaboration within the context of intra-port collaboration. Three types of vertical intra-port collaboration for cargo vessels are identified: coordination of multiple transport processes, synchronization of ITT, and the port gate control and TAS. Specifically, as introduced in Chapter 1, we only consider the connection between the port gate with the hinterland transportation, and the hinterland transportation after leaving (or before entering) the port is outside the scope of our collaborative maritime and port operations discussed in this thesis. Thus, for convenience, in the following paragraphs, we refer to trucks that move within a yard area as internal trucks, and those transporting cargo from depots to the terminal or vice versa as external trucks.

Due to the involvement of multiple logistics activities, effective coordination is of significant importance. Figure 2.2 illustrates the detailed intra-port cargo transport process. As is shown, after being unloaded from the vessels, imported containers are transported to a container yard near their following transshipment location before being transported to their hinterland destination by trucks, trails, or barges. We show that cargo can be handled at multiple positions in port terminals, though not necessarily at all, aiming to cover more potential connection situations at the port.

Coordination of multiple transport processes

A vast number of papers published have focused on studying integrated planning problems occurring on the land side of the port, such as berth allocation and quay crane scheduling [41], berth and yard template for deterministic setting [42] and uncertain considerations [43], synchronization of multiple handling facilities from the perspective of the whole terminal [44]. Recently, studies have incorporated new features associated with advanced handling facilities [45, 46] and integrated planning with automation technology [47–49].

In [45], the container operation by coordinating Tandem Quay Cranes (TQCs) with internal truck scheduling is investigated. TQCs are a new type of quay crane that can lift either four 20-foot containers or two 40-foot containers simultaneously. However, due to physical restrictions of the TQC, the containers carried by the calling vessel must be in two neighboring rows at the same tier, and the arrival of trucks that can carry these containers at the quayside must be synchronized to avoid unnecessary waiting for each other. In [46], the type of next-generation cranes that can provide services from both sides of the vessel and catch four containers at a time is considered. For ports in the transition phase from traditional cranes to the new type, the authors of [46] develop a joint scheduling model of two types of cranes. In [48], the authors study the integrated scheduling of quay cranes (QCs), yard cranes (YCs), and Automated Guided Vehicles (AGVs) at a partial automatic container terminal layout. The work of [48] only aims at the vessel loading process, while the work of [49] further incorporates both loading and unloading processes, reflecting more realistic characteristics of the automated container terminals. In [47], a new synchronous loading and unloading mode is formulated to a bi-level programming model, in which the equipment loads or unloads two containers during a round-trip operation.

Synchronization of Inter-Terminal Transport

As ports are the central meeting points connecting global freight shipping, many modal shifts happen by using the port as the intermediate hub, especially with the built-up of multiple terminals, such as deep-sea, rail, and barge terminals. This motivates ITT research regarding moving containers and cargo between organizationally separated terminals within a port [61]. This section focuses on coordinated planning among terminal operators and truck, rail, and barge operators within the scope of ITT, discussing the synchronization of multimodal transportation that happened in ITT.

The literature mainly focuses on improving the connection between the quay and the multimodal terminal, such as sea-rail [50, 51] and sea-barge [52] intermodal transportation. In [50], container handling operations by internal trucks, gantry cranes, and yard cranes are coordinated to achieve efficient ITT. In [51], the authors explore methods for optimizing the dispatch of ITT vehicles that move cargo between terminals with the objective of minimizing operational and delay costs for containers. In [52], a study on container transshipment terminals by integrating the berth and yard allocation with the schedule of the mother and feeder vessels is presented to reduce unnecessary ITT. By integrating ITT with handling operations, in [53], intermodal planning by incorporating the scheduling of vessel arrival, handling operations, and train departure is considered to facilitate seamless connections.

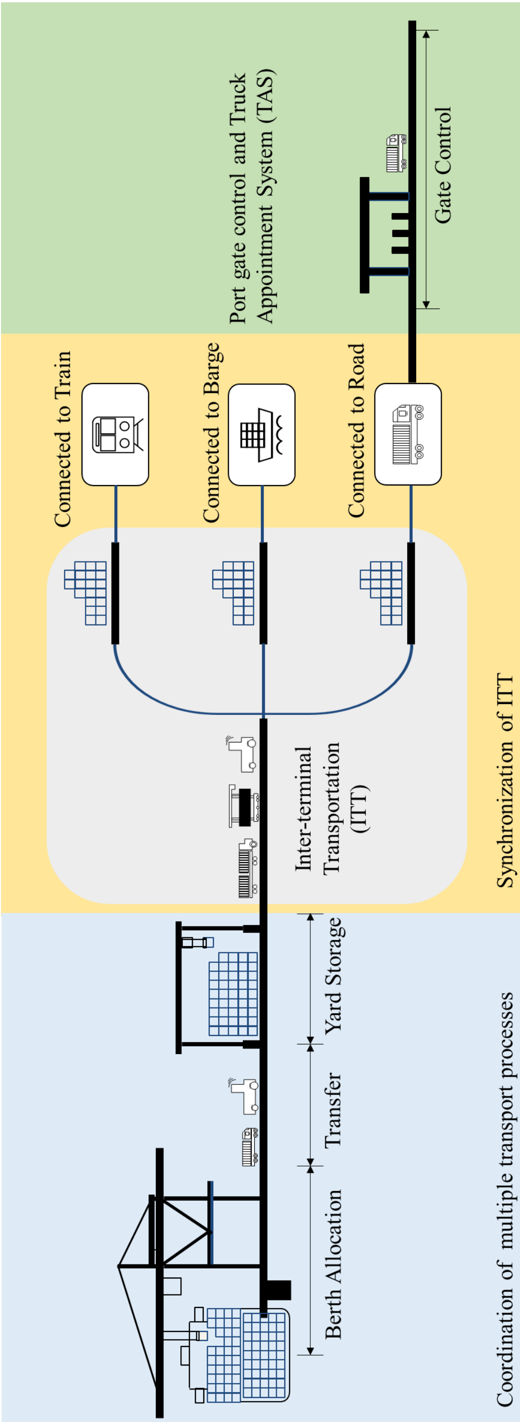


Figure 2.2: Intra-port collaboration for cargo services.

Truck Appointment Systems

The worsening port gate congestion is giving rise to many issues, such as prolonged waiting times for truck carriers and environmental pollution. The chaotic arrival of external trucks is the primary cause of gate congestion at the port. Recently, some studies, focusing on truck scheduling [54, 56] and arrival appointment [55], have demonstrated TAS as an effective solution to balance external truck arrivals with the internal workload of the port. In [54], a truck management strategy is proposed to optimize the time window allocated to truck groups by terminal operators. In [55], the authors explore the effects of implementing a booking system to reduce port gate congestion by flattening truck arrival times. In [56], a model where truck companies can update their appointment applications and the terminal responds in real-time is developed to make the model more practical.

Empty container management, including coordinating the external truck arrival with ITT vehicles [59] and enhancing container stacking plans with truck arriving announcement [57, 58], is also studied in the context of a collaborative strategy between terminal operators and truck carriers via TAS.

2.2.3 Summary

Section 2.2 overviews the past studies on vertical collaboration in maritime and port operations, showing the significant potential of developing collaborative systems in maritime shipping. However, new features supported by technological advancements (e.g., real-time information sharing) open space for innovative collaboration systems, and new models are required even for conventional problems. Therefore, this thesis aims to explore new frameworks of vertical collaboration and decision-support models that can improve the efficiency, resilience, and decarbonization of maritime and port operations.

2.3 Horizontal collaboration

Based on the participants involved, we identify four conventional forms of horizontal collaboration in maritime and port operations: shipping alliances formed by shipping lines, port coalitions formed by port operators, terminal collaboration among terminals within one port, and container drayage collaboration formed by logistics service providers. By engaging in horizontal collaboration, participants can use joint storage facilities, exchange or pool transport requests, and share the transport vehicles to maximize capacity utilization to provide service to leverage the potential economies of scale [10].

Involved participants in collaboration face a series of crucial decisions. First, they need to decide whether to join a collaboration. This problem can be concluded as selecting a coalition to join or selecting partners to form an alliance. Second, they must formulate collaborative agreements to optimize shared resources. Third, a reasonable mechanism to share costs or profits is necessary, which will also influence the formation of collaboration. Following this logic, the following section is organized as follows: the formation of collaboration in Section 2.3.1, the optimization of shared capacity in Section 2.3.2, and shared costs or profits allocation in Section 2.3.3.

Table 2.2: Relevant studies on the formation of horizontal collaboration

	Problem	Alliance S	Alliance P	Alliance T	Reference
Partner selection	Selection standards	✓			[62] [63]
			✓		[64]
	Competition and cooperation	✓			[65] [66]
				✓	[67] [68] [69]
			✓		[70] [71]
Motivation establishment	Quantative comparison with and without collaboration	✓			[72] [73]
				✓	[74] [75] [76]
	Collaborative investment	✓			[77] [78]
			✓		[79] [80] [81]

Note: S: shipping alliance; P: port coalition; T: terminal collaboration

2.3.1 Formation of collaboration

We report the relevant studies in Table 2.2, organized along two directions: partner selection with co-opetition analysis and motivation establishment. Reasonable profits or cost-sharing can also incentivize the formation of collaboration, and it will be discussed specifically in Section 2.3.3.

Partner selection and co-opetition analysis

At the formation stage, selecting a coalition or partners is important. This decides whether the collaboration can be established directly. There are some empirical studies on partner selection standards for shipping alliance [62, 63] and port collaboration [64].

However, in certain situations, competitors may also engage in collaborative efforts. Since [82] outlined the internal competition as the key factor that adversely affects the level of mutual trust within the shipping alliance, strategic analysis of competition and cooperation dynamics has been widely studied, known as the term co-opetition, in shipping alliance [65, 66], port coalitions [70, 71], and terminal collaboration [67–69].

Motivation establishment

Some papers focus on quantitative comparisons with and without joining the coalition, showing the potential benefits of collaboration. In [72], the relationship between vessel-sharing strategy and environmental performance is investigated by developing two MIP models to decide fleet deployment and container allocation under two scenarios with and without vessel sharing, and the experimental results indicate significant profit enhancement and emission mitigation. In [73], the advantage of vessel-sharing strategy is further examined in quantitatively improving empty container reuse and reducing drayage costs. In [74], the dynamics of terminals' individual profit and their willingness to cooperate are analyzed. In [75], empirical research on facilitating terminal coalitions is conducted at the Hong Kong Port, consisting of five terminal operators. [76] investigate the effects of sharing berth resources among terminals within one port using scenario simulation.

Some papers study the investment strategy to guide potential partners on whether and when to form partnerships. According to [77], the optimal investment strategy within alliances requires minimizing the number of ships required to serve the shipping network. They demonstrate extra financial benefits of carriers by incorporating competitive intensity, competitors, rate volatility, and fuel efficiency into the investment analysis. In a subsequent study of [78], low profitability and frequent alliance changes are further considered by developing a simulation model. In response to disasters, a game-theoretical model is proposed by [79] to investigate the strategic investment strategy of disaster prevention for multiple ports in the same region. In [80] and [81], the resilience of ports in the face of disasters is investigated through cross-port investments and capacity sharing in port collaboration.

2.3.2 The optimization of shared capacity

While forming alliances is recognized as a promising strategy, operating such a collaborative system effectively and efficiently presents significant challenges. Multiple papers contribute to optimizing shared capacity to maximize resource utilization. We introduce collaborative models categorized by shipping alliance, port coalitions, terminal collaboration, and container drayage collaboration. Table 2.3 presents the optimization problem, the information shared (full or limited) between partners, and the goals to achieve (profit maximization, cost minimization, decarbonization, and service level) in the literature.

Table 2.3: Optimization of shared capacity appearing in horizontal maritime collaboration

Alliance	Problem	Information sharing		Goal				Reference
		F	L	PM	CM	DC	SL	
Shipping alliance	Vessel slot allocation	✓		✓				[83] [84] [85]
			✓	✓				[86]
	Flexible shipping network	✓			✓	✓		[87] [88]
	Vessel scheduling	✓			✓	✓		[89] [90]
	Vessel train	✓			✓	✓		[91] [92] [93]
Port coalition	Inter-port BAP	✓			✓	✓		[38] [94] [95]
Terminal collaboration	Intra-port BAP	✓			✓			[96] [97] [22]
			✓		✓			[98]
	Intra-port facility sharing	✓			✓		✓	[99] [100] [101]
Container drayage collaboration	Pooling requests	✓			✓	✓		[102] [103]
	Empty container sharing		✓			✓	✓	[104] [105]
	Innovative mode		✓			✓		[106] [107] [108]
							✓	[109]
	Truck appointment system		✓		✓		✓	[110]
	Truck platooning		✓			✓	✓	[111] [112] [113]
	AGV platooning		✓				✓	[114]
Terminal collaboration	**Intra-port BAP**	✓		✓	✓		✓	**This thesis**

Note: F: full information; L: limited information; PM: profit maximization; CM: cost minimization; DC: decarbonization; SL: service level

Shipping alliances

The shipping alliance is a group of ocean carriers that join to create cooperative agreements. Over time, slot chartering and container sharing have become prevalent within shipping alliances, wherein carriers share slot capacity and (empty) containers on similar routes.

One relevant decision is the slot allocation problem, which allocates vessels' slot space for containers delivering shipments from the loading port to the discharging port on a given service route, see the work of [83–86]. In [83], an IP model is developed for slot co-allocation among carriers at the operational planning level to maximize the total revenue of the alliance. The model considers different container types between multiple port pairs on the shipping route. In [84], a multi-objective mathematical model is proposed to maximize total revenues and vessel capacity utilization simultaneously. The study of [86] aims to optimize the available space allocated to each alliance member. They incorporate stowage-plan requirements into their optimization approach, considering the presence of hazardous containers that impose additional constraints on shared vessel capacity allocation.

The slot and container sharing strategy opens opportunities for improving other relevant planning problems, such as flexible shipping network [87, 88] and collaborative vessel scheduling [89, 90] under the slot-sharing among carriers. In [87], a novel MIP model is proposed to address the liner shipping fleet deployment and repositioning problem (LSFRDP), enabling shipping alliances to establish flexible shipping networks in response to fluctuations in market demand and seasonal changes in the global economy. In [88], the authors study the fleet repositioning problem (FRP) by incorporating the optimization of freight rates and port selection to achieve maximum utility in revamping services. The model of [88] contributes to a more resilient shipping network that can effectively respond to uncertain and dynamic demands. Motivated by the operational practices of a prominent Asian container shipping company, in [89], the vessel scheduling problem under the slot-sharing agreements among carriers is studied by proposing a simplified model that can be managed by MIP, ignoring carriers' individual concerns, such as cargo types and priority. In [90], the shipping network is optimized by rescheduling the port call times based on accounting for vessel-sharing agreements and the coordination of feeder vessel services.

With the emergence of autonomous technology, the vessel train concept has been created as a new type of collaboration in the shipping alliance [91]. Typically, the vessel train comprises one leader vessel and several follower vessels that are virtually linked to moving closely behind each other using automation. In this setting, individual vessels can join and leave the vessel train at places adjacent to their points of origin and destination at the seaside or inland waterside, and vessels following the leader vessel are expected to run with significantly reduced crew staff. Therefore, it requires autonomous vessel marshaling from the operational planning perspective [92]. In [93], a MIP model is developed to decide when and where to join and leave the vessel train for individual vessels in a hub-and-spoke network. This study can be considered a crucial step toward the real implementation of vessel trains by autonomous freight ships.

Port coalition and terminal collaboration

Ports perform as the hub of maritime shipping, and one of their major tasks is to provide (un)loading services for the calling vessels. Inter-port collaboration can refer to collaboration among multiple ports in a particular region or along a specific trade route. Considering that a port may have many different terminals, and independent operators can operate these terminals, we specifically consider the cooperation of terminals within a port as terminal collaboration. In the context of port coalitions and terminal collaboration, different ports (terminals) can work together to provide the service, potentially sharing the information of the calling vessels and facilities to fully use port (terminal) resources [115].

For port operators, port capacity can not be moved physically from one port to another due to geographical restrictions. Thus, relevant studies focus on sharing the service requirements of the calling vessels among collaborative ports. For example, the calling vessels can call at the coalitional ports instead of waiting at the initially planned port. Berths are significant resources that can impact port capacity directly, therefore, which obtained much research interest, see the work of [38, 94, 95]. In [38], a multi-port BAP allowing vessels to change the calling sequence of the port is proposed, which indicates the port coalition among ports along the predefined route. Then, a discrete and a continuous berthing layout of BAP are explored in [94] and [95], and an exact method based on the branch-and-price algorithm for large-scale discrete BAP and an adaptive large neighborhood search (ALNS) heuristic for continuous setting are developed, respectively.

For terminal operators, many papers focus on shared resource allocation for terminal collaboration, such as berths, internal trucks, and yard space. In [96], a BAP model allowing vessels to transfer to another terminal is first proposed to minimize the total service time. In [97], a berth allocation and quay crane assignment problem (BACAP) is considered in a collaborative setting of the intra-port coalition, where the ITT cost caused by vessel reassigning between terminals and the vessel tardiness reduction is balanced in the objective function. In [22], the transshipment operations between feeder vessels and mother vessels are incorporated when implementing vessel reassignment in BACAP within the concept of terminal collaboration. The study of [67] formulates a conceptual BAP model under uncertainty using the collaborative approach. In [98], a decentralized cooperative method is developed for BAP by grouping individual carriers and sharing information among group partners.

In terms of intra-port facility sharing, in [99], numerical experiments are conducted for resource-sharing strategies among five terminals of Hong Kong Port, evaluating the terminal performance improvement concerning costs, service level, and operation efficiency by terminal collaboration. Besides quay-line resources, the land-side facility sharing among terminals within one port also receives increasing research interest. In [100], a collaborative internal truck scheduling problem is studied using a simulation optimization method. In [101], a multi-objective MIP model for internal truck allocation in ITT is developed based on truck sharing among terminals.

Container drayage collaboration

The container movement by trucks (or other vehicles, such as AGVs) between a customer's depot location and a container terminal is defined as the container drayage operation [116]. Container drayage operations account for a significant portion of the total cost in maritime container shipping. Typically, the independent organization of container pickup and delivery incurs many unproductive trips.

Although collaboration is not mentioned directly, many papers optimize truck scheduling based on pooling or clustering different container drayage requests. In [102], a truck scheduling problem is studied in container drayage operation with multiple depots and terminals, which is graphically formulated into a multi-depot asymmetric multiple traveling salesman problem with time windows (m-TSPTW) whose objective is to minimize the total transport time of all trucks. In [103], the authors develop a deterministic annealing algorithm and demonstrate its satisfying performance on both results and computation time. In [106], a new variant of the vehicle routing problem (VRP) is developed with clustered backhauls into a linear programming formulation, where the deliveries (importers) in each route must be satisfied before pickups (exporters). In [110], a collaborative approach to internal truck scheduling for container drayage is proposed based on TAS by capacity sharing among trucking companies to reduce the transportation of empty trucks, which reduces costs and emissions. The work of [110] offers new insights into the traditional TAS, focusing on reducing congestion at seaports and truck turnaround times.

In terms of empty container sharing, in [104], the authors further incorporate the empty container sharing so that the empty depot belonging to one truck company can also serve other truck companies if the budget is reduced. In [105], an exact column-and-row generation approach embedded in a branch-and-price framework is proposed to accelerate the solving process of the mathematical model.

For innovative modes, studies of [107] and [108] use tractors and trailers to transport the container, in which the tractor and the trailer can be separated and connected with each other. Other than sharing the requests, the empty containers are also shared among stakeholders who issued the transport requests. In [109], the productivity improvement of a collaborative tractor-and-trail mode in US container drayage operations and its reduction impact on air emissions is evaluated.

The concept of truck platooning has recently also gained heightened interest. A truck platoon is formed by a leading truck followed by a set of trucks using semi-automated technologies. The flexibility of platooning, such as multiple types of marshaling and empty container sharing, can significantly reduce costs and emissions of container drayage operations [117]. To make a platoon mode more flexible, the work in [112] enhances the coordination between the platoon and other transportation modes by allowing the trucks connected initially to their respective leading trucks to move to alternative transport modes for performing subsequent tasks, and in [114], a new approach is proposed base on applying AGV platoons to fulfill container drayage requests.

2.3.3 Shared costs and profits allocation

Incentives for individual partners are crucial for forming a coalition and maintaining collaboration stability. Costs or profits allocation problems, referred to as payoff allocation, have been widely investigated from a game theoretical perspective in collaborative freight and logistics. Because the potential co-opetition mainly exists in horizontal collaboration, most relevant studies are aimed at horizontal collaboration rather than vertical collaboration. In Table 2.4, we categorize the studies by the approaches they applied to allocate payoffs, and we also report the properties of the allocation method and indicate whether the study considers a centralized or decentralized way. Although there are no substantial studies exclusively aiming at maritime shipping, some theoretical methods appear inspiring for collaborative maritime and port operations, and thus we also include these studies.

Table 2.4: Payoff allocation in collaborative transportation

Method	Type		Property			Area		Reference
	C	D	F	S	U	G	M	
Shapley Value	✓		✓		✓	✓		[118] [119]
							✓	[94]
Core	✓			✓		✓		[120] [121]
Nucleolus	✓			✓	✓	✓		[122]
							✓	[25]
Derived method	✓		✓	✓		✓		[123] [124]
							✓	[125] [126]
Comparison	✓		✓	✓	✓	✓		[127] [128]
							✓	[129]
Core	✓			✓			✓	**This thesis**
Nucleolus	✓			✓	✓		✓	**This thesis**

Note: Type: C: centralized; D: decentralized; Property: F: fairness; S: stability; U: uniqueness; Area: M: maritime; G: general freight transportation)

Cooperative Game Theory

In the cooperative game theory, Shapely Value, the Core, the Nucleolus, and the derivative methods based on these concepts are widely applied to horizontal collaboration stability and fairness problems [21].

The directly relevant studies on maritime and port operations are limited, see [25, 94, 125, 126, 129]. Much more work is found within a broad concept of transportation while inspiring a lot for promoting collaboration in maritime transport, and we briefly conclude them as follows: Shapley Value for fairness [118, 119], The Core for stability [120, 121], The Nucleolus for maximum stability [122], and other derived approaches [123, 124]. No method is shown to be better than the others, depending on the application case. Thus, some papers compare the above-introduced costs or profits allocation methods, see [127, 128].

2.3.4 Summary

Section 2.3 overviews the past studies on horizontal collaboration in maritime and port operations. Similarly, this thesis aims to explore innovative forms of horizontal collaboration in maritime shipping. Most existing studies assume that the collaboration has already been established, ignoring the incentives and stability of the collaboration. Thus, other than collaborative planning models, this thesis also aims to provide methods for incentivizing individual members to join the partnerships.

2.4 Conclusions

This chapter comprehensively reviews the collaborative approaches in maritime and port operations studies. We identify and analyze key collaboration types, main stakeholders, and the corresponding collaborative planning models with OR techniques. It addresses our research question **Q1**: “What are the characteristics and key challenges of collaborative maritime and port operations?” and **Q2**: “How do OR methodologies contribute to the decision-making of collaborative systems in maritime and port operations?”

To reap the benefits of collaborative strategies for maritime shipping, innovative forms and new supporting models to deal with more efficient, advanced, and flexible collaboration are still required.

The research gaps are identified as follows:

1. Resource-sharing collaboration inherently opens up new spaces for decision-making optimization while simultaneously introducing novel OR challenges. For terminals, berths and quay cranes are both crucial resources, and their capacity limits the efficiency of port operations. Therefore, it is imperative to propose innovative collaboration forms and develop corresponding planning models. Further, to enhance the resilience of maritime shipping, models with more practical considerations are required in response to disruptions. In Chapter 3 and 4 of this thesis, we address this gap. In detail, we investigate an innovative berth planning approach based on horizontal collaboration in Chapter 3, and an integrated berthing model is proposed as a complement to the forms of vertical collaboration in Chapter 4.

2. From the practical standpoint, it is imperative to identify effective incentive schemes of collaboration at the profit-based level, with a focus on the interests of individual stakeholders, to ensure collaboration stability. Specifically in horizontal collaboration, the collaborative members are often competitive simultaneously. In such a setting, collaboration incentives become essential to decision-support models for collaborative planning. These models need to be developed at an operational planning level and applied dynamically. Game Theory has been demonstrated effective for many collaborative freight transportation problems, while the application dedicated to the maritime domain is very limited. In Chapter 5, we bridge this research gap by designing attractive and stable allocation schemes.

3. Existing studies mainly focus on optimizing the slow steaming of vessels and port handling operations to reduce unnecessary fuel costs, thereby contributing to decarbonization. Although this approach has proven effective, its impact remains constrained in its capacity to reduce emissions. The ambitious goal of “carbon-neutral” by 2050 urges governments, researchers, and maritime practitioners to pay close attention to decarbonization towards net-zero emissions. In Chapter 6, we address this gap by providing operational support for establishing green corridors and proposing a new concept based on applying green fuels (e.g., liquid natural gas, hydrogen, ammonia, and so on) to achieve zero emissions in maritime shipping.

Chapter 3

A Collaborative Berth planning Approach for Disruption Recovery

As Chapter 2 concludes, to enhance the resilience of maritime shipping, it is important to explore innovative collaboration forms and develop corresponding planning models with more practical considerations in response to disruptions.

This chapter addresses the research question **Q3**: "How does collaboration work as a means for efficient and resilient port operations?". For terminals, berths and quay cranes are both crucial resources, and their capacity limits the efficiency of port operations. To ally different terminals to share berthing resources is a promising solution to further improve efficiency and enhance resilience. Therefore, this chapter investigates a collaborative variant of the berth allocation recovery problem which focuses on the collaboration among terminals and transshipment connections between vessels.The results from the performed computational experiments, considering multiple scenarios with disruptive events, show consistent improvements for the suggested collaborative strategy.

This chapter is organized as follows. Section 3.1 introduces the research background. Section 3.2 presents the related literature, and Section 3.3 explains the model formulation. Section 3.4 develops the SWO-based heuristic, and Section 3.5 conducts computational experiments. Section 3.6 gives managerial implications. Section 3.7 presents the conclusions, summarizing the major findings.

This chapter has been published in *IEEE Open Journal of Intelligent Transportation Systems* [1].

3.1 Introduction

International maritime trade has been greatly increasing over the last decades, and the global container port throughput reached its peak, 811.2 million Twenty-foot Equivalent

[1] X. Lyu, R. R. Negenborn, X. Shi, F. Schulte, A collaborative berth planning approach for disruption recovery, IEEE Open Journal of Intelligent Transportation Systems 3(2022) 153–164.

Units (TEU) in 2019 [1]. These large volumes require efficient and robust quay-side operations for the calling vessels. Providing a quick and reliable berthing plan while minimizing costs and congestion is important for both shipping lines and terminal operators. Because changing the configuration of terminals (e.g., extending the quay) needs a rather expensive investment, improving the efficiency of available berths and quay cranes is essential for terminals to remain competitive. The berthing plan determines when and where to load or discharge containers for the calling vessels as well as the number of quay cranes to be allocated. Generally, terminal operators form a weekly berthing plan before the calling of vessels. However, there are frequent disruptions (e.g., vessel arrival delay or extreme weather) hindering the execution of the initial plans. Thus, uncertainties cannot be ignored, and a well-functioning berthing plan should incorporate both efficiency and disruption recovery [130].

Current research deals with uncertainties from two main perspectives, namely proactive and reactive. Proactive strategies focus on anticipating the uncertainty and variability of the real-world scenarios before the disruption [131, 132]. These scenario-based research are important in the long run, but terminal operators also need instant decision-making support [133]. Thus, this chapter studies reactive strategies that aim to make quick and effective responses to disruptions. Reviewing the literature on reactive strategies, researchers tend to prioritize larger vessels in response to disturbances, but they mostly ignore the implied transshipment connections between vessels. Containers that are discharged from one vessel and then loaded on another vessel may delay the transshipment because of the uncoordinated berth planning. Moreover, during major disruptions, some calling vessels have to wait a long time until the berths and quay cranes are idle.

Collaboration has been identified as a win-win strategy for both collaborating terminals [134], especially when terminals confront major disruptions. This strategy reduces the waiting time of disrupted vessels by allying different terminals to share berthing resources, that is, allowing the calling vessels to transfer to other terminals. Vessel transfer between terminals may cause much inter-terminal and intra-terminal cost, but it can relieve the congestion caused by disruptions in the current terminal.

Cooperative decisions and collaboration among terminals have been considered in the berth planning problem in [97, 135]. To the best of our knowledge, studies on collaborative berth planning among terminals are limited, not to mention the disruption management model. In addition, authors of [134, 136] consider transshipment connections between feeder and mother vessels under deterministic assumptions. However, research has not yet investigated disruptions for the berthing plan from this more realistic perspective, that is, considering transshipment connections and the collaboration among terminals together.

In this chapter, we develop a collaborative berth planning model for terminals in response to disruptions. BAP is an NP-hard problem, and commercial solvers cannot find optimal solutions in an acceptable time for large-scale instances of the problem. Therefore, we propose Squeaky Wheel Optimization (SWO)-based metaheuristic and conduct computational experiments that demonstrate that the new collaborative approach can yield cost savings of up to 40% for disruption recovery. The main contributions of this chapter are as follows:

1. We propose a new reactive berth allocation and quay crane assignment problem from a more practical perspective, which considers transshipment connections between

feeder and mother vessels. Furthermore, we incorporate the collaboration among terminals by allowing vessels to transfer to other terminals in response to major disruptions;

2. We establish a new Mixed Integer Non-Linear Programming (MINLP) model for the proposed problem, and then we linearize it;

3. We design a dedicated, efficient, and effective SWO-based metaheuristic to solve large-scale instances of the proposed mathematical model, which can obtain near-optimal solutions within the limited time;

4. The reactive and collaborative berth planning method provides new insights on terminal operators to better respond to disruptions.

3.2 Related work

Traditional berth planning for vessels to call at the container terminals requires making a sequence of decisions. To support the decision-making process, researchers have developed various models and methods based on operation research techniques, especially the integration of the problems, namely, the Berth Allocation and Quay Crane Assignment Problem (BACAP) and Berth Allocation and Quay Crane Scheduling Problem (BACSP). Readers may refer to [41, 137, 138] for comprehensive reviews. In bulk terminals, there are also similar decision-making problems, such as the integration of berth and ship-unloader allocation [139], and the coordination of rake schedule and stockyard operation [140]. The problem addressed in this paper can be referred to as the BACAP including when and where to conduct loading and unloading operations with how many quay cranes for each calling vessel. Relevant studies can be found firstly in [141]. The authors divide the scheduling method into the berth-scheduling phase and crane-assignment phase. In the berth-scheduling phase, the duration of berthing time is directly determined by the number of allocated quay cranes and the subgradient optimization technique is proposed to find a near-optimal solution. The result is applied as the input in the crane-assignment phase. Then some more practical considerations and algorithms have been incorporated in BACAP. In [142], the authors consider the different rates of quay cranes because their productivity can be reduced by the interference among quay cranes. Meta-heuristics of Tabu Search (TS) and Squeaky Wheel Optimization (SWO) are proposed to obtain near-optimal solutions. In [143], the authors loose the restriction on not allowing adjustment of quay cranes during the loading or unloading operation and increase the restrictions on the operation range of quay cranes. In [144], the authors propose a coupling BACAP to minimize not only the service time of vessels but also the number of quay crane shifts. In [145], the authors consider tide factors in berth allocation. In [146], the authors consider a longer planning horizon and propose the tactical BACAP. In [147], the authors especially consider that the demand for quay crane hours is increasing with the deviation from the desired berthing position. As for the heuristics, other than mentioned above, Adaptive Large Neighbourhood Search (ALNS) is proposed in [148]. In [149], the authors focus on the exact algorithm for BACAP. An exact Branch-and-Price (BP) as well as several accelerating schemes have been proposed and examined to outperform commercial solvers.

The research above is based on deterministic information of calling vessels, while many uncertainties exist in reality. In [150], the authors analyzed the key factors associated with the efficiency of seaside logistics based on the case of the Indian shipping logistics sector. Their work contributes to getting researchers connected with the practical scenarios. Compared with the extensive literature on berth planning under normal conditions, the studies on responding to disruptions (e.g., uncertain vessel arrival time and quay crane breakdown) are limited. These topics related to the robustness and resilience of maritime logistics systems, however, are now generating considerable recent interest. In response to disruptions, there are two mainstream approaches: proactive and reactive. Some proactive concepts and models have been designed for robust planning to disturbances. In [151], the authors insert time buffers between vessels allocated to the same berthing position to obtain more adjustment flexibility under disruption. In [152], the authors extend the time buffer to vessel-specific buffer times to chase for a higher robustness performance. In [153], the authors propose a robust initial berth plan which incorporates not only anticipation of the uncertainty of arrival time and handling time but also possible recovery cost under practical disruption scenarios. The concept is further applied in [154] which considers both uncertain vessel arrival times and quay crane handling rates. In [132], the authors develop a bi-objective model by minimizing the average and the total service time simultaneously. In [155], the authors firstly propose an initial plan which especially considers quay crane productivity and formulate a robust optimization model with price constraints to deal with the uncertainty of quay crane handling time. For container terminals, a higher degree of robustness generally means a higher possibility of underused berth or quay crane resources. Thus, some studies directly relevant to this paper study the reactive approaches, which means making recovery decisions once the disturbances occurred. Its focus is to mitigate the adverse effects brought by disruptions. In [133], the authors formulate quay crane rescheduling model and berthing position reallocation model according to the degree of disruptions. In [156], the authors consider the early dispatch service under disruptions for some vessels that require early departure and the corresponding profits can be seen as the compensation for recovery cost. In [157], the authors propose a recovery berth plan based on the scheme of updating arrival and handling time in real time. In [158], the authors also regard the baseline schedule as a reference and propose a Mixed-Integer Programming (MIP) to minimize the cost incurred by the deviation from the baseline. In [136], the authors additionally consider the transshipment connection between feeder and mother vessels during the recovery process and try to avoid the delay of transshipment flows caused by disruptions.

Table 3.1: Related work for robustness and resilience of the berth and quay crane planning to major disruptions

Reference	Handling Scheme		Considered Disruption			Special Consideration		Uncertainty Representation		Method			Berth Type		Research Problem		
	P	R	UA	UH	QB	TR	CP	SS	PD	M	RO	SP	D	C	BA	BACAP	BACSP
[133]		*	*					*		*				*		*	*
[159]	*	*	*	*				*	*			*		*	*		
[151]	*		*	*				*		*				*	*		
[132]	*		*	*				*		*			*		*		
[156]		*	*	*			*	*		*				*		*	
[30]		*			*		*	*		*				*			*
[160]	*		*	*				*				*	*		*		
[157]		*	*	*					*	*			*		*		
[161]	*		*	*			*	*		*			*			*	
[158]		*	*	*	*			*		*			*			*	
[162]	*		*						*			*		*	*		
[163]	*	*	*	*				*			*			*	*		
[154]	*	*	*	*				*	*			*		*		*	
[97]		*					*	*		*				*			*
[136]		*	*			*		*		*				*		*	
[22]		*	*	*	*	*	*	*		*				*		*	

P: proactive; R: reactive;
UA: uncertainty of arrival time; UH: uncertainty of handling time; QB: quay crane breakdown;
TR: transshipment between feeder and mother vessels; CP: collaborative planning;
SS: scenario simulation; PD: probability distribution;
MIP: mixed integer programming; RO: robustness optimization; SO: stochastic programming;
D: discrete; C: continuous;
BA: berth allocation problem; BACAP: berth allocation and quay crane assignment problem;
BACSP: berth allocation and quay crane scheduling problem

Berths and quay cranes are both precious resources in container terminals and the configuration cannot be changed in short-term horizons. Thus, under major disruptions, the responding strategy has to sacrifice the turnaround time of vessels because of the limitation of resource capacity. To overcome this, some models of collaborative planning by increasing the collaboration among multi-user terminals have been proposed. In [135], the authors develop a joint berth scheduling through cooperation between adjacent terminals when an unexpected shutdown happened in a terminal. A decentralized mechanism is proposed based on the flexible scheme of transfer payment adjustment. In [97], the authors propose a new mathematical model for BACAP in a multi-user terminal in which the transfer of vessels to other terminals is allowed through collaboration among them. In [38], the authors propose a collaborative berth planning based on strong collaboration between port terminals and shipping lines from the perspective of the shipping network. For all sailing legs between the nodes in the network, the speed of each vessel can be optimized to reduce total fuel consumption.

Although the concept of collaboration has been applied in liner shipping studies, most of them view the berth allocation at a strategic or tactical management level. There is limited amount of research considering collaborative berth planning from the operational level in response to disruptions. As is shown in Table 3.1, this paper addresses the reactive BACAP that incorporates the transshipment connections between vessels and collaboration among terminals by allowing vessels to transfer to other terminals. Delay of vessel arrival time and handling time, quay crane breakdown, and unexpected shutdown of the terminal are considered in scenario analysis to testify our model and metaheuristic.

3.3 Problem definition

In this section, we first present the reactive BACAP allowing vessels to transfer to other terminals in the context of major disruptions, in which the transshipment connections between feeder and mother vessels are simultaneously considered. Next, we introduce the MINLP model for generating a recovery plan with the minimized cost of deviation from the original one. Assumptions that are in line with the practice needed in our study are listed as follows:

1. The operation process for each vessel is conducted without interruption, which means quay cranes are not allowed to move to other vessels when they are at work.

2. The number of quay cranes that work on the same vessel simultaneously is restricted by a minimum number and the maximum number. The minimum number is based on the agreement between terminal operators and vessel companies, and the maximum number is limited by technical operation requirements.

3. This paper considers a continuous BAP at container transshipment terminals, which involves the import, export, and transshipment operations.

4. This paper is based on the setting of multi-user terminals. Dedicated terminals are not considered in the proposed problem because the resources cannot be shared for the dedicated terminals that belong to one exact shipping company.

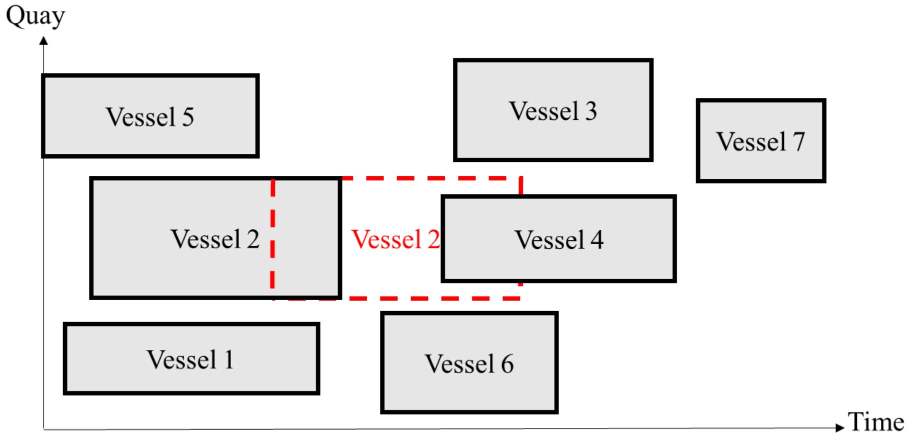


Figure 3.1: Initial berthing plan under the disruption

3.3.1 Problem description

Consider the scenario where the disruptions (e.g., vessel arrival delay, quay crane breakdown, and so on) make the initial berthing plan into trouble, affecting the loading or discharging operations of one or a few vessels. As illustrated in Figure. 3.1, the delay of the initial plan for Vessel 2 causes the plan for Vessel 4 invalid, and some adjustment for the initial plan is needed. For container terminals, rescheduling the berthing plan at a lower cost as well as reducing the disturbance to the whole system incurred by disruptions is important. Thus, the objective of the studied reactive berthing problem mainly considers minimizing the cost of space deviation and time deviation from the original plan.

For some instances where exist transshipment connections between vessels, the delay of operation for vessels has to be specially considered. As shown in Figure. 3.2, the transshipment from Vessel 2 to Vessel 7 cannot be fulfilled as planned, which causes unnecessary holding costs of the delayed containers. In Figure 3.3, the transshipment between Vessel 2 and Vessel 7 can be satisfied by adjusting Vessel 3 and Vessel 7, which is at the cost of a higher deviation from the initial plan. Facing major disruptions, as shown in Figure 3.4, Vessel 2 is also allowed to transfer to other terminals to eliminate the disturbance to the current terminal. However, reassigning vessels to other terminals incurs the extra cost of inter-terminal and intra-terminal transportation. For simplicity, we refer to the terminals that vessels could be transferred to from their original ones as complementary terminals.

As mentioned above, the post-disruption berthing plan needs sophisticated decision-making support. The challenge is how to make a trade-off between the deviation cost, the transshipment delay cost, and the transfer cost. Thus, the objective function in this paper consists of three parts. The first part presents the deviation cost of berthing position and the tardiness of departure time. The second part considers the penalty cost of transshipment delay between vessels. The third part regards allowing vessels to transfer to other terminals. The number of quay cranes is also reassigned during the process simultaneously.

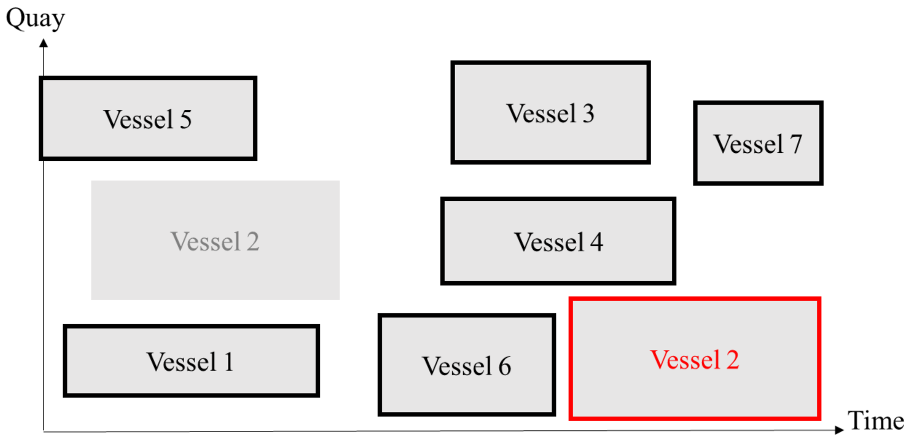


Figure 3.2: Reactive berthing plan without considering the transshipment connection

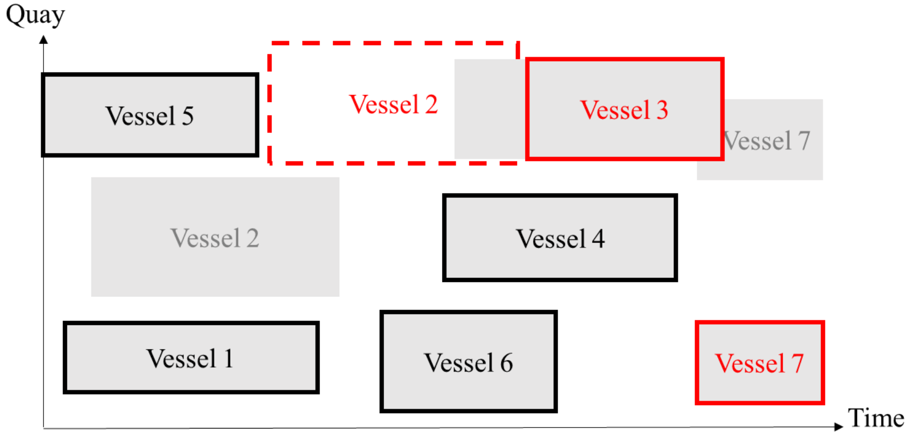


Figure 3.3: Reactive berthing plan considering the transshipment connection

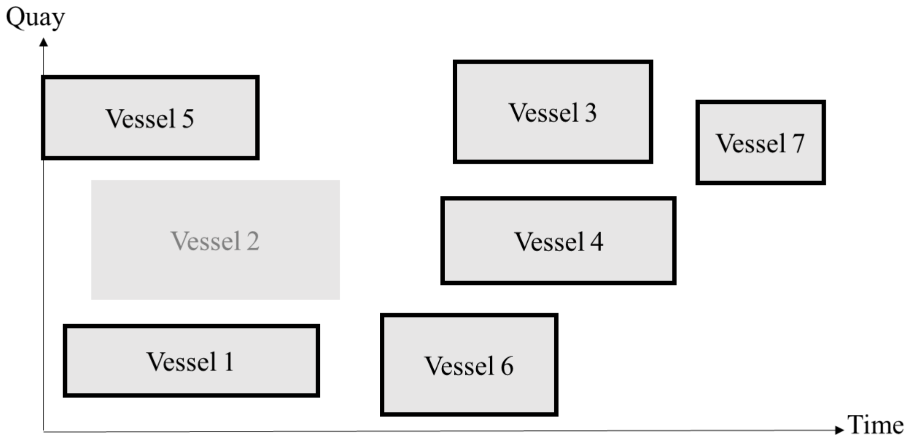


Figure 3.4: Reactive berthing plan by transferring Vessel 2 to the other terminal

3.3.2 Model formulation

Following the notation of the earlier paper [136], we define the notations for mathematical modelling in this chapter at Table 3.2.

Based on the above notations, the reactive model for the collaborative berth planning problem is formulated as follows:

$$\begin{aligned} \min \quad z = & \sum_{i \in V} c_1 g_i |b_i - b_i'| \\ & + \sum_{i \in V} c_0 (CT_i' - CT_i - M \sum_{p \in P} k_{ip})^+ \\ & + \sum_{i \in V} \sum_{j \in V} c_2 d_{ij} \lambda_{ij} + \sum_{i \in V} \sum_{p \in P} c_3^p g_i k_{ip} \end{aligned} \tag{3.1}$$

Subject to:

$$c_1 g_i |b_i - b_i'| \leq M(1 - \sum_{p \in P} k_{ip}) \quad \forall i \in V \tag{3.2}$$

$$\sum_{p \in P} k_{ip} \leq 1 \quad \forall i \in V \tag{3.3}$$

$$\sum_{i \in V} k_{ip} \leq MAX_p \quad \forall p \in P \tag{3.4}$$

$$\sum_{t \in T} \gamma_{it} = CT_i' - ST_i' \quad \forall i \in V \tag{3.5}$$

$$AR_i \leq ST_i' < CT_i' \quad \forall i \in V \tag{3.6}$$

$$ST_i' \leq \gamma_{it} t + M(1 - \gamma_{it}) \quad \forall i \in V, t \in T \tag{3.7}$$

$$CT_i' \geq \gamma_{it}(t+1) \quad \forall i \in V, t \in T \tag{3.8}$$

Table 3.2: Notation of sets, parameters, and decision variables used in Chapter 3.

Notation	Explanation
Sets	
V	set of all vessels, $V = \{0, 1, \cdots, \|V\|\}$.
V_1	Set of mother vessels, $V_1 \subset V$.
V_2	Set of feeder vessels, $V_2 \subset V$.
T	Set of one-hour time periods, $T = \{0, 1, \cdots, \|T\|\}$.
I	Set of transshipment flows, $I = \{0, 1, \cdots, \|I\|\}$.
P	Set of complementary terminals, $P = \{0, 1, \cdots, \|P\|\}$.
Parameters	
c_0	Time cost of delay for each period.
c_1	Unit cost of horizontal moving of containers.
c_2	Penalty cost for missing of transshipment flow.
c_3^p	Extra cost incurred by transferring a vessel to terminal $p \in P$.
l_i	Length that vessel $i \in V$ will occupy.
b_i	The berthing position of vessel $i \in V$ in the initial plan.
d_{ij}	20-ft equivalent units required to be operated from vessel $i \in V$to vessel $j \in V$.
w_i	QC capacity demand by vessel $i \in V$ given as number of QC-hours.
q_i^{min}	Minimum number of QCs needed to serve vessel $i \in V$.
q_i^{max}	Technically maximum number of QCs allowed to serve vessel $i \in V$.
MAX_p	Maximum number of vessels that can be transferred to terminal $p \in P$.
g_i	Total 20-ft equivalent units required to be loaded or discharged on vessel $i \in V$.
Δ	The time interval of preparing for transshipment operation.
AR_i	Actual arriving time of vessel $i \in V$.
ST_i	Initial operation start time of vessel $i \in V$.
CT_i	Initial operation completion time of vessel $i \in V$.
Q	Total number of available QCs in the terminal.
L	Length of the quay.
Decision variables	
$b_i^{'}$	Actual berthing position of vessel $i \in V$.
$x_{ij} \in \{0, 1\}$	1 if vessel$i \in V$ is berthed on the left of vessel $j \in V$ in the space dimension, and 0 otherwise, $i \neq j$.
$y_{ij} \in \{0, 1\}$	1 if vessel $j \in V$ is berthed after the operation of vessel $i \in V$ in the time dimension, and 0 otherwise, $i \neq j$.
$\gamma_{it} \in \{0, 1\}$	1 if at least one QC is assigned to vessel $i \in V$ at time$t \in T$, and 0 otherwise.
$\lambda_{ij} \in \{0, 1\}$	1 if transshipment flow from vessel$i \in V$ to vessel $j \in V$ is missed, and 0 otherwise,$i \neq j$.
$k_{ip} \in \{0, 1\}$	1 if vessel $i \in V$ is transferred to terminal $p \in P$, and 0 otherwise.
$ST_i^{'} \geq 0$	Actual operation starting time of vessel $i \in V$.
$CT_i^{'} \geq 0$	Actual operation completion time of vessel$i \in V$.
$q_{it} \geq 0$	Number of QCs assigned to vessel $i \in V$ at time $t \in T$.

$$\sum_{t \in T} q_{it} \geq w_i(1 - \sum_{p \in P} k_{ip}) \quad \forall i \in V \tag{3.9}$$

$$\sum_{i \in V} q_{it} \leq Q \quad \forall t \in T \tag{3.10}$$

$$M(\gamma_{it} - 1) - q_{it} < 0 \quad \forall i \in V, t \in T \tag{3.11}$$

$$q_{it} \leq M\gamma_{it} \quad \forall i \in V, t \in T \tag{3.12}$$

$$q_{it} \geq 0 \quad \forall i \in V, t \in T \tag{3.13}$$

$$q_{it} \geq \gamma_{it} q_i^{min} \quad \forall i \in V, t \in T \tag{3.14}$$

$$q_{it} \leq q_i^{max} \quad \forall i \in V, t \in T \tag{3.15}$$

$$b_i' + l_i \leq b_j' + M(1 - x_{ij}) + M \sum_{p \in P} k_{ip} \quad \forall i \in V, j \in V, i \neq j \tag{3.16}$$

$$CT_i' \leq ST_j' + M(1 - y_{ij}) + M \sum_{p \in P} k_{ip} \quad \forall i \in V, j \in V, i \neq j \tag{3.17}$$

$$x_{ij} + x_{ji} + y_{ij} + y_{ji} \geq 1 - M \sum_{p \in P} k_{ip} \quad \forall i \in V, j \in V, i \neq j \tag{3.18}$$

$$M(\lambda_{ij} - 1) - (CT_i' + \Delta - ST_j') < M \sum_{p \in P} k_{ip} \quad \forall i \in V, j \in V, i \neq j \tag{3.19}$$

$$M\lambda_{ij} - (CT_i' + \Delta - ST_j') \geq -M \sum_{p \in P} k_{ip} \quad \forall i \in V, j \in V, i \neq j \tag{3.20}$$

$$\lambda_{ij} \leq M(1 - \sum_{p \in P} k_{ip}) \quad \forall i \in V, j \in V, i \neq j \tag{3.21}$$

$$0 \leq b_i' \leq L - l_i \quad \forall i \in V, j \in V \tag{3.22}$$

$$x_{ij} \in \{0,1\} \quad \forall i \in V, j \in V \tag{3.23}$$

$$y_{ij} \in \{0,1\} \quad \forall i \in V, j \in V \tag{3.24}$$

$$\lambda_{ij} \in \{0,1\} \quad \forall i \in V, j \in V \tag{3.25}$$

$$\gamma_{ij} \in \{0,1\} \quad \forall i \in V, j \in V \tag{3.26}$$

$$k_{ip} \in \{0,1\} \quad \forall i \in V, j \in V \tag{3.27}$$

$$ST_i' \geq 0 \quad \forall i \in V \tag{3.28}$$

$$CT_i' \geq 0 \quad \forall i \in V \tag{3.29}$$

The above equations are further developed based on [136] and [130]. The objective function (3.1) aims to minimize the total cost of the reactive berthing plan. This cost includes spatial deviation from the initial plan, departure tardiness, penalties for transshipment delays between correlated vessels, and extra costs from reassigning vessels to collaborative terminals. Constraint (3.2) states that the deviation cost and transshipment delay cost for Vessel i can be avoided by collaborating with other terminals. Constraint (3.3) limits that there is only one chance to transfer to another collaborative terminal for each Vessel i. Constraint (3.4) satisfies the terminal p's maximum number of receiving the vessels being transferred from other terminals. Constraints (3.5)-(3.8) show the definition of the berthing end time of Vessel i and the berthing start time of Vessel i. Constraint (3.9) ensures that the QC-hour requirements for Vessel i can be met after adjustment. Constraint (3.10) ensures that the number of QCs assigned at time t does not exceed the total available number. Constraints (3.11)-(3.14) restrict the relationship between variables q_{it} and γ_{it}. Constraints (3.15) restricts the maximum number of QCs that can be assigned to each Vessel i. Constraint (3.16) denotes the relationship between berthed vessels in the dimension of space. Similarly, constraint (3.17) states that relationship in the time dimension. Constraint (3.18) ensures that no overlapping exists in berthing time and berthing position. Constraints (3.19) and (3.20) are the definition of λ_{ij}. Constraints (3.22) states the berthing position limitation by the length of quay line. Constraints (3.23)-(3.29) specify the range of decision variables.

The terms of calculating deviation of the berthing position and tardiness of the departure time in the objective function (3.1) and constraint (3.2) are nonlinear. Thus, they need to be linearized by defining an additional decision variable $\theta_i = |b_i - b_i'|$ and $\xi_i = (CT_i' - CT_i)^+$. The related additional constraints are defined as follows:

$$\theta_i \geq b_i' - b_i - M \sum_{p \in P} k_{ip} \quad \forall i \in V \tag{3.30}$$

$$\theta_i \geq b_i - b_i' - M \sum_{p \in P} k_{ip} \quad \forall i \in V \tag{3.31}$$

$$\xi_i \geq CT_i' - CT_i - M \sum_{p \in P} k_{ip} \quad \forall i \in V, p \in P \tag{3.32}$$

$$\theta_i \leq M(1 - \sum_{p \in P} k_{ip}) \quad \forall i \in V \tag{3.33}$$

$$\xi_i \geq 0 \quad \forall i \in V \tag{3.34}$$

$$\theta_i \geq 0 \quad \forall i \in V \tag{3.35}$$

Therefore, the reactive model for collaborative berthing plan problem can be reformulated as a mixed integer linear program as follows:

$$\begin{aligned} \min \quad z = & \sum_{i \in V} c_1 g_i \theta_i + \sum_{i \in V} c_0 \xi_i \\ & + \sum_{i \in V} \sum_{j \in V} c_2 \lambda_{ij} d_{ij} + \sum_{i \in V} \sum_{p \in P} c_3^p g_i k_{ip} \end{aligned} \tag{3.36}$$

Subject to Constraints (3.3) - (3.35).

3.4 Solution approach

The BAP has been recognized as an NP-hard problem. Compared with BAP, the proposed reactive berthing plan problem extends to consider vessel transfer between terminals and vessel-to-vessel transshipment as well as quay crane assignment, which should also be an NP-hard problem. Exact solution are only achievable for small-scale instances and maybe not practical for solving large-scale problems. SWO has demonstrated effective performance in solving related problems (as described in Section 3.2) whose objective function consists of multiple individual elements. In this work, the objective function represents the total cost for rescheduling the berthing plan after disruptions, which can be decomposed into the cost of each vessel during the rescheduling process. Therefore, the SWO-based heuristic method is developed.

3.4.1 SWO-based heuristic framework

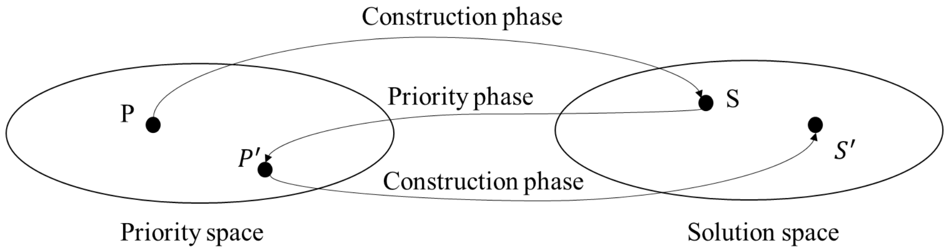


Figure 3.5: Principle of the SWO Algorithm

The idea of the SWO-based heuristic approach is to search solutions through two-phase (construction phase and priority phase) in two spaces: priority space and solution space, as shown in Figure. 3.5. In the studied problem, a point in the priority space denotes an order of vessels for resource allocation and a homologous point in the solution space represents the potential solutions. The construction phase is to find a set of feasible solutions under the given processing order for vessels, and then update the point in the priority space by priority phase, in which the order of vessels is reassigned according to the cost of each vessel. The principal is the vessels with higher costs are assigned a higher priority. SWO schemes to explore better solutions via a coherent shift in the priority space and solution space iteratively. The outline of the solution framework is presented in Algorithm 1.

Algorithm 1: General framework of the SWO-based heuristic

1: Initialization: baseline parameters relevant to BAP
2: **repeat**
3: Construction phase: obtain feasible solution $(b_i^{'}, CT_i^{'}, k_{ip})$
4: Calculate the individual cost z^i:

$$c_1 g_i |b_i - b_i'| + c_0^i (CT_i' - CT_i)^+ + c_2 \sum_{j \in V} d_{ij} \lambda_{ij}$$

5: Priority phase: generate a new order $inseq^{'}$
6: **until** Termination criteria
7: Stop
Output: $(b_i^{'}, CT_i^{'}, k_{ip})$, and z^i

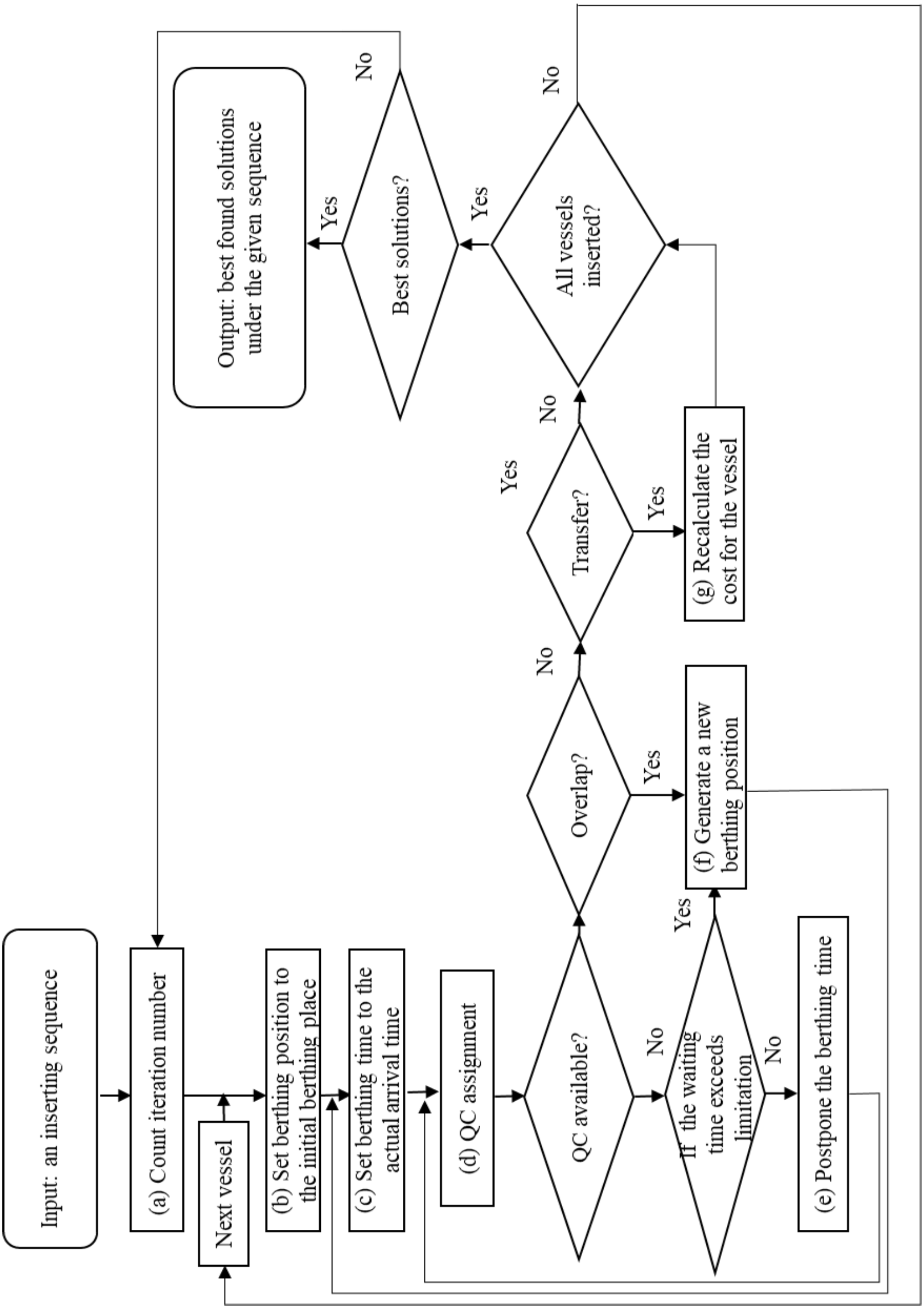


Figure 3.6: Construction phase

3.4.2 Construction phase

The procedure in the construction phase is shown in Figure. 3.6. In Step (a) the iteration number is counted. In Step (b) and (c) the berthing position of Vessel i is set as the baseline and the berthing time is set to the actual arrival time. If the available number of quay cranes is larger than q_i^{min}, in Step (d) the number of quay cranes is allocated to Vessel i to handle the vessel as fast as possible until Constraint (3.9) holds. If the available number of quay cranes is less than q_i^{min} before satisfying Constraint (3.9), the quay crane assignment stopped. Postponing the berthing time in Step (e) and the quay crane assignment is then reallocated by returning to Step (d), which incurs a longer waiting time for Vessel i after arrival but guarantees no deviation of the berthing position. Certainly, the waiting time should not be too long so if it exceeds the limitation, a new berthing position is generated in Step (f) and return to Step (c). Because the large deviation of the berthing position from the original one means the great cost of horizontal moving of containers, the new berthing position is restricted in$[b_i - l_i b_i + l_i]$. After the quay crane assignment of Vessel i is finished, the completion time for Vessel i can be fixed and one vessel has been arranged already. Then check whether the vessel overlaps with other vessels in the space-time diagram. If there is no overlapping, compare the cost of rescheduling Vessel i with transferring Vessel i to other terminals, choose one with less cost in Step (g). Arrange next Vessel $i^{'}$ until all the vessels have been inserted. Otherwise, the arrangement of Vessel i will be processed again from the new generation of berthing positions. Once the berthing position and quay crane assignment for all vessels are determined, the total cost can be calculated according to function (3.1). Then return to Step (a) to start the next iteration until the maximum iteration times. Finally, the construction phase returns the best-found solutions under the current given order of vessels.

3.4.3 Priority phase

The point of the priority phase is to find a neighborhood sequence for the given order of vessels. The basic idea is swapping the sequence of two vessels if the higher priority vessel makes less contribution regarding overall cost than the lower priority one: choose two Vessels i and j from the last iteration, compare the objective value z^i and z^j. If Vessel i is inserted before Vessel j and $z^j \geq z^i$, then these two Vessels i and j should be swapped and a new order is generated accordingly. An example is shown in Figure. 3.7. Generally, the concept of SWO is to figure out the 'bottle neck' elements which contribute a relatively large proportion to the objective value and then to give them higher priority during resource allocation to search for better solutions. Thus, after the priority phase, the vessel with the largest cost obtained in the construction phase should have the highest priority in the new order of vessels and so on.

3.5 Computational study

The SWO-based heuristic is running on a PC with 1.70 GHz CPU and 8 GB RAM under C++ environment. The mathematical model is solved by CPLEX12.8 and running time is reported in seconds. In this section, the instance generation and experimental parameters are introduced firstly. And then we design comprehensive computational experiments in

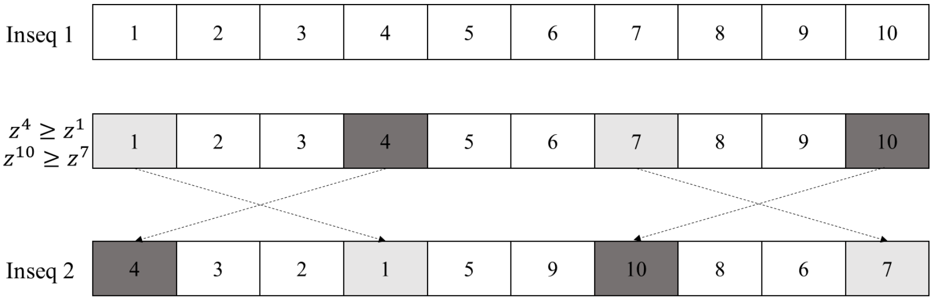


Figure 3.7: Priority phase

order to assess the efficiency and effectiveness of the proposed mathematical model and the SWO-based heuristic.

3.5.1 Generation of instances

The detailed attributes of three-vessel types (Feeder, Medium, and Jumbo) are generated according to Table 3.3. In addition, the number of transshipment containers between feeder and mother vessel d_{ij} is generated in accordance with industry standards. The number of the collaborative terminals is distinct in different scenarios, but it is not more than 5. We restrict the number of collaborative terminals to no more than 3. The post-disruption BACAP planning horizon is one week (168 h) and the length of the quay side is set as 3250m. The time interval for preparing for transshipment between vesselsδ is 10. Other parameters related to the cost are set as $c_1 = 0.01$, $c_2 = 0.2$, $c_0 = 30$. The terminated iteration number of the SWO heuristic is 1000.

Table 3.3: Vessel types and related attributes

Types	l_i(m)	w_i(qc*hour)	q_i^{min}	q_i^{max}	TEU
Feeders	U[8,21]	U[4,15]	1	2	U[500,3500]
Mother-Medium	U[21,30]	U[15,36]	1	4	U[3500,5000]
Mother-Jumbo	U[30,40]	U[36,48]	3	6	U[5000,7500]

3.5.2 Results on small-scale instances

Table 3.4 presents the total cost given by SWO-based heuristics and CPLEX (with the model proposed in Section 3). The instances include 15 vessels, in which 5 mother vessels, 10 feeder vessels and the number of transshipment flow between feeder and mother vessels is 10. The proportion of vessels facing operation delays due to disruptions is 20%, 40% and 60% and their delay time is set as 5, 10, 15 respectively. For the results obtained by CPLEX, the objective value is denoted by z^{MIP} and the computational time is reported. For the SWO-based heuristic, we report the similar information and the total cost during the post-disruption rescheduling is denoted by z^{SWO}. The last column in the table represents the gap percentage between the MILP solution and SWO solution, which is calculated by:

$$\frac{|Z^{SWO} - Z^{MIP}|}{Z^{MIP}} \times 100\% \tag{3.37}$$

As shown in Table 3.4, the proposed SWO-based heuristic is able to obtain high quality solutions for the small-scale problem with 15 vessels and 10 transshipment flows between vessels.

Table 3.4: Results of SWO-based heuristic with Cplex

Delay Proportion	Instance Id	Delay hours	Cplex		Swo		Gap
			z^{MIP}	Time	z^{SWO}	Time	
20%	Data_I1	5	622.6	0.8	622.6	3.84	0%
	Data_I2	10	772.6	0.73	772.6	3.06	0%
	Data_I3	15	944.2	0.46	944.2	3.02	0%
40%	Data_I4	5	672.6	0.67	672.6	2.99	0%
	Data_I5	10	1309.34	0.96	1309.34	4.88	0%
	Data_I6	15	1559.34	0.69	1559.34	4.82	0%
60%	Data_I7	5	822.6	0.75	822.6	2.98	0%
	Data_I8	10	1609.34	0.75	1609.34	4.91	0%
	Data_I9	15	1122.6	0.57	1122.6	2.95	0%

3.5.3 Improvement from allowing vessels transfer to collaborative terminals

We also conduct some experiments to testify the effectiveness by allowing vessels to transfer to collaborative terminals when disruptions happened. As shown in Table 3.5, we generate four instance sets with different number of vessels and it varies between 15, 21, 28, and 40, for example, there are 28 vessels in Set 3, in which 8 mother vessels, 20 feeder vessels, and 20 transshipment connections occur.

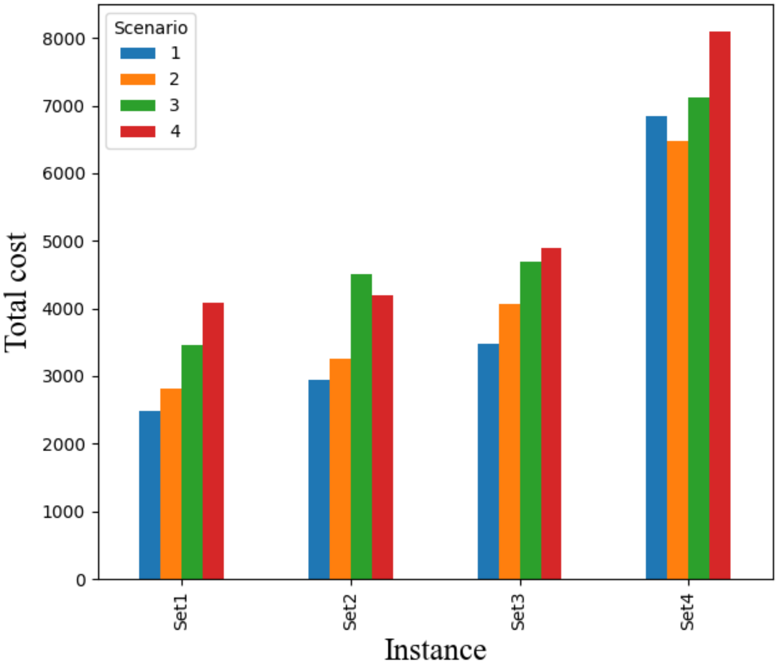
Table 3.5: Instance parameters

Instance	$\|V\|$	$\|V1\|$	$\|V2\|$	$\|I\|$
Set 1	15	5	10	10
Set 2	21	6	15	30
Set 3	28	8	20	40
Set 4	40	10	30	60

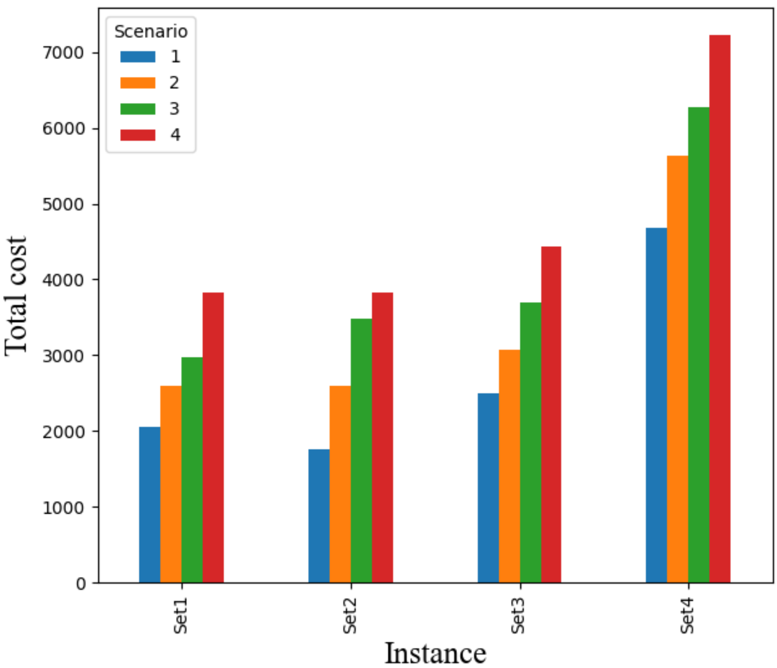
Four disruption scenarios are generated. In Scenario 1, 30% of vessels are delayed to be operated because of vessel arrival delay and quay crane breakdown. The proportion is 35%, 40% and 50% in Scenario 2, Scenario 3 and Scenario 4 respectively. Set1-01

Table 3.6: Results of SWO-heuristic with and without considering collaboration between terminals

Instance ID	Without collaboration		With collaboration		Improvement (3)
	Total cost(1)	Time	Total cost(2)	Time	
Set1-01	2490.80	3.00	2055.76	11.12	17.47%
Set1-02	2810.80	2.83	2597.26	5.91	7.60%
Set1-03	3450.80	2.99	2964.90	11.74	14.08%
Set1-04	4090.80	4.86	3822.28	7.76	6.56%
Average	-	-	-	-	11.43%
Set2-01	2935.80	3.43	1759.35	13.11	40.07%
Set2-02	3255.80	3.67	2592.28	10.62	20.38%
Set2-03	4513.40	3.56	3480.48	14.07	22.89%
Set2-04	4193.40	3.75	3821.80	10.59	8.86%
Average	-	-	-	-	23.05%
Set3-01	3485.80	5.92	2498.51	19.07	28.32%
Set3-02	4061.80	6.10	3074.51	19.44	24.31%
Set3-03	4701.80	6.10	3691.23	19.49	21.49%
Set3-04	4893.80	7.16	4431.96	20.37	9.44%
Average	-	-	-	-	20.89%
Set4-01	6850.68	8.98	4674.82	32.43	31.76%
Set4-02	6474.27	8.59	5626.80	29.90	13.09%
Set4-03	7114.27	8.55	6266.80	29.85	11.91%
Set4-04	8097.70	8.57	7226.80	30.27	10.75%
Average	-	-	-	-	16.88%



(a) Without collaboration



(b) With collaboration

Figure 3.8: Total cost with collaboration and without collaboration

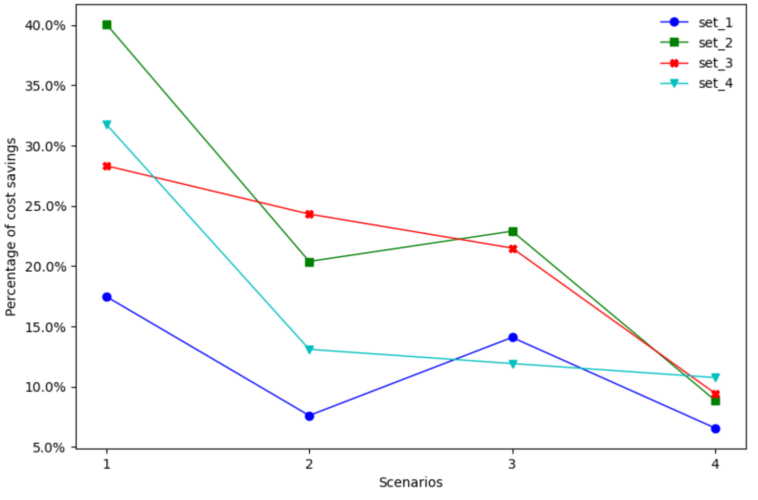


Figure 3.9: Percentage of cost savings in four scenarios by considering collaboration

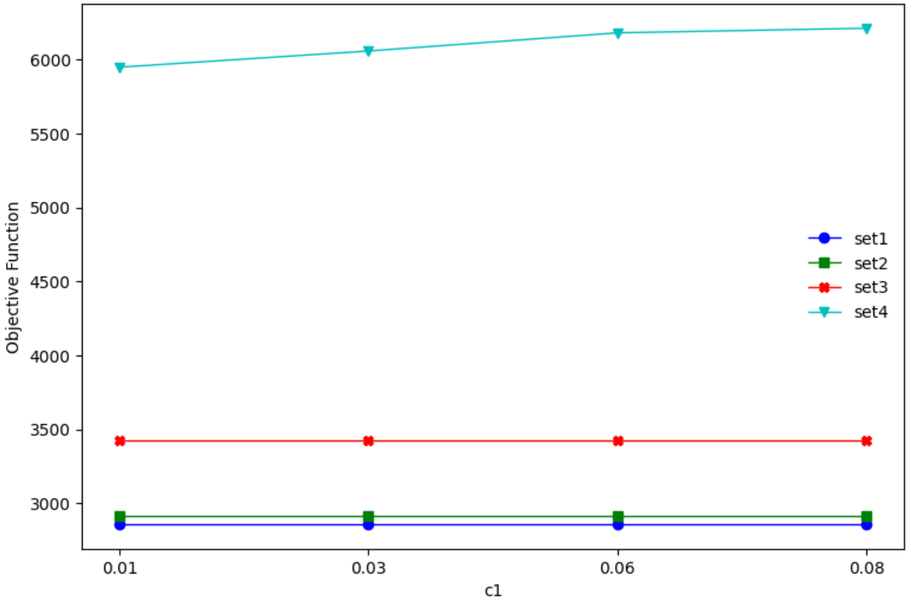
means the instance Set 1 under Scenario 1. The results obtained by the SWO-heuristic with and without considering collaboration between terminals are presented in Table 3.6 and Figure. 3.8. The percentage of cost savings of four sets in four scenarios are obviously shown in Figure. 3.9. During the post-disruption rescheduling process for berthing plan, allowing vessels to transfer to other terminals can help to save 40% of the total cost at most. Thus, it is concluded that considering vessels transfer between terminals via collaboration is meaningful in response to disruptions.

3.5.4 Parameter sensitivity analysis

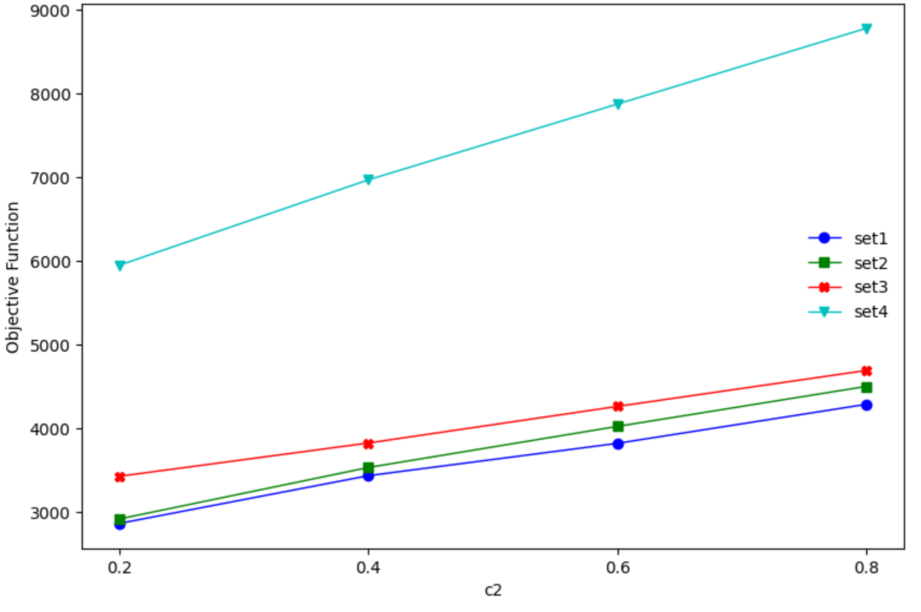
The unit cost of horizontal moving of containers c_1 and penalty cost for delaying transshipment flow c_2 affect the final results. Hence, we analyze the two parameters to show their influence on the objective function. In Figure.3.10(a), c_1 is set from 0.01 to 0.08, c_2 is kept at 0.1. It is shown that c_1 has a slight impact on objective function in Set 1-3 while a relatively significant influence in Set 4. These results show that larger container terminals are more sensitive to the price for horizontal container moving. In Figure. 3.10(b), c_1 is set as 0.01 while c_2 varies from 0.2 to 0.8. The results show that c_2 has a larger impact on the objective function than c_1. For container terminal operators, they can estimate the corresponding recovery cost according to the different penalties of transshipment delay, so as to make reasonable decisions on disruption recovery.

3.5.5 Measuring the cost of resilience

The recovery cost with collaboration is lower than without collaboration, which means the terminal operators pay less in response to disruptions by considering collaboration. To some extent, cost savings can be used to measure resilience. Thus, we applied the metrics proposed by [164]:



(a) Impact of parameter c_1



(b) Impact of parameter c_2

Figure 3.10: Impact of parameter c_1 and c_2 on the objective function

$$R = \frac{\sum_u^d C_u(t) - \sum_u^d \sum_m C_u^m(t) - \sum_m C_m(t)}{\sum_u^d C_u(t)} \tag{3.38}$$

Here, $\sum_u^d C_u(t)$ is the summation of recovery cost at time t under disruption d without any resilience mechanism and $\sum_u^d \sum_m C_u^m(t)$ represents the corresponding sum of recovery costs with resilience mechanism m. $\sum_u^d \sum_m C_u^m(t)$ is the cost associated with the investment of mechanism m. R values from 0 to 1. $R = 1$ implies perfect resilience while $R = 0$ implies less resilience to disruption. In this paper, we can simplify (3.38) into the following formulation:

$$R = \frac{\sum_u^d C_u(t) - \sum_u^d C_u^{wc}(t)}{\sum_u^d C_u(t)} \tag{3.39}$$

In our case, the mechanism is considering collaboration among terminals and the investment associated with the mechanism (extra cost incurred by transferring a vessel to terminal) has been calculated into the recovery cost $\sum_u^d C_u^{wc}(t)$. Figure.3.11 shows different R under different instances from Set1 to Set4.

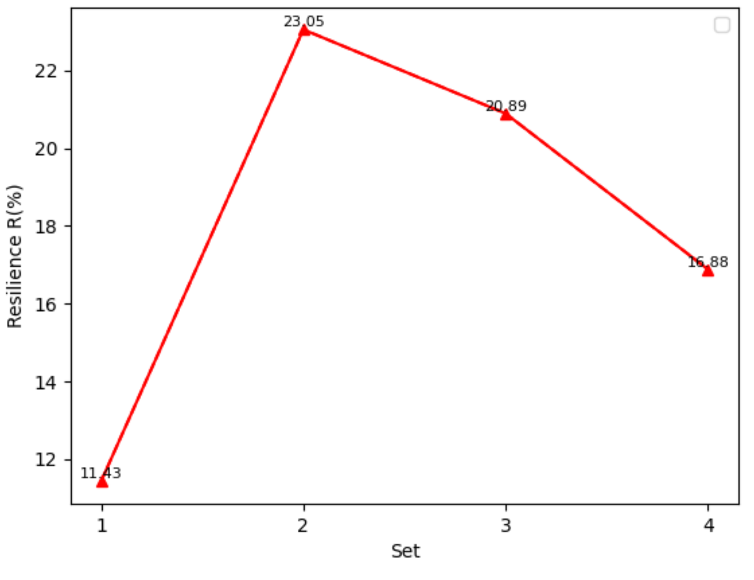


Figure 3.11: Different R under different instance set

3.6 Discussion

In this paper, we propose a collaborative berth planning approach to decide when and where the calling vessels should be berthed and which quay cranes should be assigned after disruptions occurred. With computational experiments considering four disturbance scenarios and we obtain several managerial insights for terminal operators and policy implications for handling disruptions at ports:

1. Our experiments show that the average cost savings brought by collaboration among terminals are in the range of 11.43%-23.5%. Therefore, terminal operators should consider establishing some forms of collaboration to allow integrated berthing plans to minimize disruptions and reduce recovery costs. For instance, in some disruption cases where the number of berths or quay cranes fails to satisfy the calling vessels, some vessels could be transferred to other terminals. Of course, the extra cost caused by transferring vessels depends on the agreement with the collaborative terminals and there is a trade-off between service level and service cost for the disrupted terminals.

2. The percentage of cost savings in scenario 1 where the delayed proportion is 30% is greatly higher than in scenario 4 that is 50% disturbance. The results are reasonable because it is difficult to recover the berthing plan when the terminal gets into disruption. But in most cases, for instance, when the disturbance percentage is less than 50%, it is important to take measures at the operational level to prevent the terminal from getting congested. Otherwise, terminal operators need to resort to some high-level planning measures (e.g., speeding up vessels or changing the calling ports), which will involve more adjustments.

3. The proposed SWO-based metaheuristic is able to provide effective decision support for terminal operators within 60 seconds, which is meaningful in practice because compared to predicting the occurrence of disturbances, a rapid post-disruption recovery plan is more needed.

4. In the proposed approach, the operation time for each vessel is affected by the number of allocated quay cranes to reflect the systematic nature of the berth planning problem. Thus, terminal operators should employ an integrated mathematical model to make decisions, for instance, the integrated berth allocation and quay crane scheduling.

5. Traditional rules for disruption recovery such as First-Come-Fist-Service and Large-Vessel-First cannot work well in practice, especially in container transshipment terminals [156]. The delayed containers that should be transshipped between feeder and mother vessels in this period not only occupy the resources of terminals but also incur extra costs. Thus, terminal operators should take into consideration the transshipment connections when rescheduling the original berthing plan to avoid the implied cost.

3.7 Conclusions

The research trend on berth planning has shifted from deterministic models to models with uncertainty considerations reflecting the increasing importance of disruptive events in the real world. In [133] and [154], for instance, the authors propose two disruption recovery models in response to disruptions according to different scenarios. However, these studies mostly assume that each terminal makes its own independent plans, that is, the berthing plan of incoming vessels can only be adjusted within the current terminal when the disruption happens. In this work, we propose a collaborative berth planning approach for disruption recovery that explicitly considers collaboration between the terminals, allowing vessels to transfer to other terminals and transshipment connection between vessels. For the proposed MINLP model, the commercial solver, CPLEX, has been used to find the optimal solutions, and an SWO-based heuristic is presented for treating problems of larger size. Numerical experiments show that the SWO-based metaheuristic can obtain solutions (near)-optimal solutions for small-scale problems, and it provides solutions within the time requirements when the instance size grows. These results add to the research on the berth planning recovery problem, confirming the effectiveness and efficiency of the proposed model and metaheuristic. Most importantly, the experimental comparisons show that the collaboration between terminals helps to save up to 40% of the total recovery cost. Therefore, our findings indicate that allying terminals to share berthing resources is a potential solution in response to disruptions. To the best of our knowledge, this is the first work to consider the transshipment connections between vessels as well as the collaboration between terminals for berth planning recovery problems. Our results show a significant potential for establishing and exploring forms of collaboration between terminal operators to achieve higher-level performance on efficiency and reliability.

This chapter proposes a collaborative berth planning approach based on terminal coalitions belonging to horizontal collaboration forms, showing its performance in enhancing resilience in maritime shipping. In the next chapter, the vertical collaboration form regarding the berth allocation problem is identified and the corresponding decision-support model is developed in Chapter 4.

Chapter 4

An Integrated Berthing Strategy for Bulk Terminals with Unavailability and Stock Level Constraints

This chapter addresses the research question **Q3**: "How does collaboration work as a means for efficient and resilient port operations?" by proposing an integrated berthing strategy from the vertical collaboration perspective. In this chapter, we explore an integrated berthing planning problem specific to bulk terminals, where both berth allocation and inventory management decisions are jointly optimized. This approach considers key operational constraints, such as berth unavailability and stock level requirements, ensuring a cooperative decision-making process that effectively improves port operations.

The organization of this chapter is as follows. Section 4.1 introduces the research background and Section 4.2 provides an overview of the relevant research. Section 4.3 develops a mixed-integer optimization model for the hybrid collaborative berth allocation problem dedicated to bulk terminals. In addition to considering the handling characteristics of bulk terminals, we also incorporate more practical factors such as unavailability and stock levels. The objective of the proposed model is to minimize the demurrage fee for all vessels under consideration of unavailability and stock constraints. In Section 4.4, we use the commercial software CPLEX to obtain the optimal solutions for a set of distinct instances, explicitly considering the situation of multiple cargo types on one vessel. Based on the quantitative results, we also present managerial insights. Section 4.5 concludes the chapter.

This chapter has been published in *Proceedings of 13th International Conference on Computational Logistics* [23][1].

[1]X. Lyu, F. Schulte, Hybrid berth allocation for bulk ports with unavailability and stock level constraints, in: Proceedings of 13th International Conference on Computational Logistics, Barcelona, Spain, 2022, pp. 3–15.

4.1 Introduction

Over the past decades, the tonnage of bulk cargo carried by sea shipping has increased sharply. Based on [165], in 2020, the international dry bulk trade and tanker trade was 8.085 billion tons, accounting for 75.9% of the world's total cargo load. The ever-growing demand makes efficient loading or discharging of vessels a great challenge, and it has generated many research interests recently. Generally, the Berth Allocation Problem (BAP) is concerned with the optimal decisions on assigning a berthing position and berthing time to the calling vessels. Operation Research (OR) methods and techniques contribute significantly to the BAP in container ports and provide strong managerial support for port managers [166, 167]. However, research dedicated to BAP in bulk ports has received relatively little attention.

Although the BAPs in bulk ports are similar to those in container ports, some unique characteristics differentiate them. A significant difference is that the bulk vessels can only be allocated to the berthing position where the installed handling equipment can serve the cargo type on the vessel. In other words, berth assignments at bulk ports are more restrictive than container ports. In [168], they establish innovative models and solution algorithms specifically for BAP in bulk ports, which highlights the specific features of bulk port operations, that is, the cargo type of vessels and the equipped handling facilities of berths. Furthermore, the cargo type restricts the berthing position and influences the service starting and completion time. For instance, specific cargo can be discharged from the vessel only when its storage places can accommodate the corresponding quantity. The study of [169] models stock level constraints but not consider the time-variant property of the stock that is changing with the loading or discharging process. Besides, in [170] and [171], they stress that the unavailability of berths frequently appears in practice because of extreme weather or maintenance requirements. However, few studies have focused on the BAP model for bulk ports with stock level restrictions, let alone combing it with unavailability considerations.

This chapter presents a Mixed-Integer Programming (MIP) model for the hybrid BAP in bulk terminals, which explicitly considers the constraint of time-variant stock level and practical unavailability. We use the commercial software CPLEX to obtain solutions for a set of instances, and the results show the effectiveness of the proposed model.

4.2 Related work

Operational problems related to BAP have been widely investigated within the context of container ports. For more details, we recommend readers to refer to [41] and [138].

The layout of the terminals is generally categorized as discrete, continuous, and hybrid. As shown in Figure. 4.1, in the continuous BAP, the calling vessels can berth at any position along the quay line. In the discrete BAP, the quay line is separated into different berths, and the calling vessels can only occupy at most one berth. Obviously, the continuous case can better use the quay, but it also increases calculation complexity. While the hybrid BAP allows the continuous case and the discrete case to happen simultaneously; thus, it is more flexible. In Table 4.1, we list the related work on BAP in bulk ports. We group them according to four feature categories: objective, type, method, and practical considerations. Two different main objectives are identified: time-based and cost-based. Type refers to three

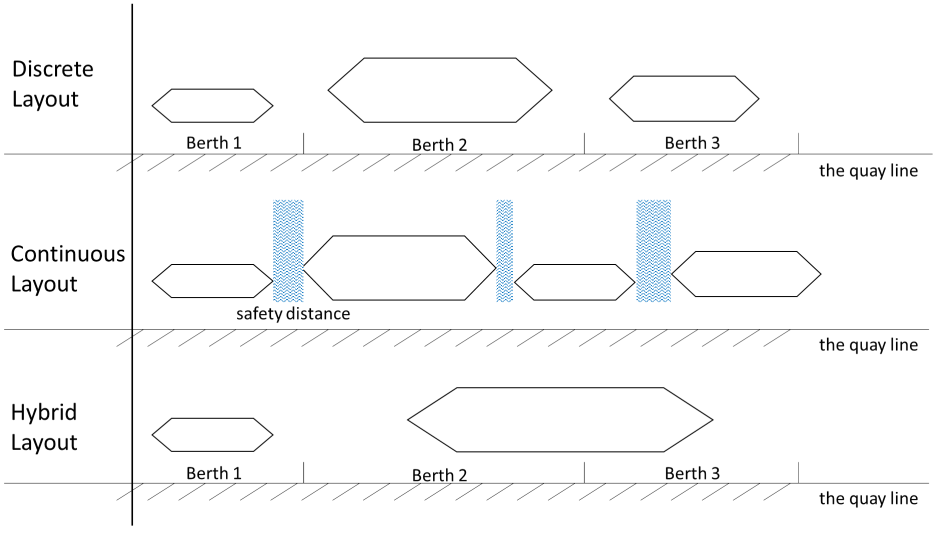


Figure 4.1: Three types of the berthing layout.

layouts as illustrated in Figure. 4.1. The solution method can be divided into heuristics or exact algorithms. The practical considerations include the integrated problem, stock level, night operation permission, specific cargo type, unavailability, and tidal constraints.

Some studies focus on the optimization of individual berth allocation. In [172], they model and solve the hybrid BAP in bulk ports to minimize the duration time of all vessels. In bulk ports, specialized equipment is required to handle specific types of cargo; for instance, liquid bulk is generally discharged using pipelines installed at only certain sections along the quay. Thus, the BAP model for bulk ports has to incorporate the cargo type on the vessel and the handling equipment fixed on the berths. The authors propose an exact solution based on generalized set partitioning and a heuristic method based on squeaky wheel optimization to obtain near-optimal solutions for the large problem size. Some practical factors that can influence the decision-making process of berth allocation have been considered in the literature. The work of [173] and [174] address the continuous BAP considering the constraints of tides which can influence the departure time of full loaded vessels. Since the stock level of the specific cargo type must be kept in some range for safety consideration, the decision to load or discharge vessels should also consider stock level. An integer linear programming model based on discrete BAP is proposed by [169], which considers not only tidal effects but also the stock level. A Simulated Annealing-based (SA) algorithm is designed to find reasonable solutions for difficult instances. Then, in [175], the authors propose a continuous BAP model with the objective to maximize the daily throughput of the terminal and, at the same time, minimize the delay of ships' departure. In fact, all the studies mentioned above aim to minimize the berthed time of vessels. In [171], they present a discrete BAP with the objective to minimize the costs (demurrage) incurred. The maintenance of the berth, another practical factor, is also considered in the model, which means that some berths cannot receive vessels at a particular time.

The other operational problems are often interrelated to the decisions of berth allocation;

thus, there are some papers studying integrated BAP. Studies of [136] and [22] focus on the integrated problem of berth allocation and handling equipment assignment, but they are focused on container transshipment terminals. In [176], the authors address the integrated berth allocation with handling equipment assignment. In [139], a Decision Support System (DSS) is developed for the port authority to make decisions on berth and ship unloader assignment to minimize the waiting time, operating time, and ships priority deviation. Studies of [177] integrate the BAP with yard management by considering constraints of the storage position in berth allocation operation. Real bulk port data is used to validate the model, and the results show that the model can work with up to 40 vessels within reasonable computational time. In [178], the authors discuss how to combine the berth and yard assignment to be a single large-scale optimization problem with the objective to minimize the total service time for all vessels berthing at the port. A branch-and-price algorithm is proposed to solve the integrated problems. A novel machine learning-based system to coordinate the berthing and yard activities is proposed in [179]. Based on that, they also insert vessel-specific buffer time to increase the robustness of the results in response to disruption [180]. In [181], the authors establish a systematical planning model from berth allocation to yard storage in dry bulk terminals. They also incorporate the tidal time windows in the modal to increase the applicability of the proposed method in real-world terminals. Following the trend of sharing economy, some scholars have seen the potential of collaboration among terminals within one port [182]. The continuous BAP [183] and the discrete BAP [170] are further studied for multiple continuous quays in bulk terminals.

4.3 Model formulation

This section first describes the berth allocation process in bulk ports and then introduces the relevant notations. Next, it develops a Mixed-Integer Programming (MIP) model and the linearized formulation.

4.3.1 Problem description

Figure. 4.2 shows an illustrative example of the process for berth allocation in bulk ports. In this context, we consider a set of vessels $N = \{1,2,\ldots,|N|\}$ that will call at the port within the planning horizon $T = \{0,1,\ldots,|T|\}$. We discrete the quay into a set of berths $M = \{1,2,\ldots,|M|\}$. The berth features (e.g., length, draft, and installed equipment) limit the vessels they can serve. We define M_i to represent the set of berths that vessel i can be served. In practice, the stock level of each cargo type has to be satisfied during loading or discharging operations. For example, the vessel cannot be discharged if the terminal's stock level of the corresponding cargo carried by some vessels would exceed the capacity, even though the berth is idle. These vessels can only wait until there is sufficient capacity. Determined by the length of the vessels and berths, we allow one vessel to occupy two berths simultaneously. Some unavailability constraints may arise due to weather conditions or facility breakdown; for instance, cranes must undergo planned maintenance in order to stay in a good performance. To sum up, the hybrid BAP model for bulk ports in this paper incorporates the following points:

(1) One vessel is allowed to occupy two berths under the setting of the hybrid layout.

Table 4.1: An overview related to the literature on the BAP in bulk ports

Reference	Objective		Type			Method		Feature					
	Time	Cost	D	C	H	ES	HS	I	S	N	M	U	T
[176]	✓		✓			✓		✓					
[173]	✓			✓		✓							✓
[184]	✓		✓			✓							
[169]	✓		✓				✓		✓				✓
[172]	✓				✓	✓	✓				✓		
[178]	✓		✓			✓		✓					
[139]	✓	✓	✓				✓	✓					
[175]	✓			✓			✓						
[181]	✓		✓			✓		✓					
[182]	✓	✓	✓			✓	✓	✓					
[174]	✓			✓			✓						✓
[171]		✓	✓				✓					✓	
[183]	✓			✓			✓	✓					✓
[170]		✓		✓			✓	✓				✓	
[185]	✓	✓	✓				✓	✓					
[177]		✓			✓	✓		✓				✓	
[179]	✓		✓				✓						
[180]	✓		✓				✓				✓		
[23]		✓			✓	✓			✓	✓	✓	✓	

Type: D: Discrete; C: Continuous; H: Hybrid;
Method: ES: Exact Solution; HS: Heuristic Solution;
Feature: I: Integrated with other problems; S: Stock level; N: Night operation permission; M: Multiple cargo types on one vessel; U: Unavailability; T: Tide;

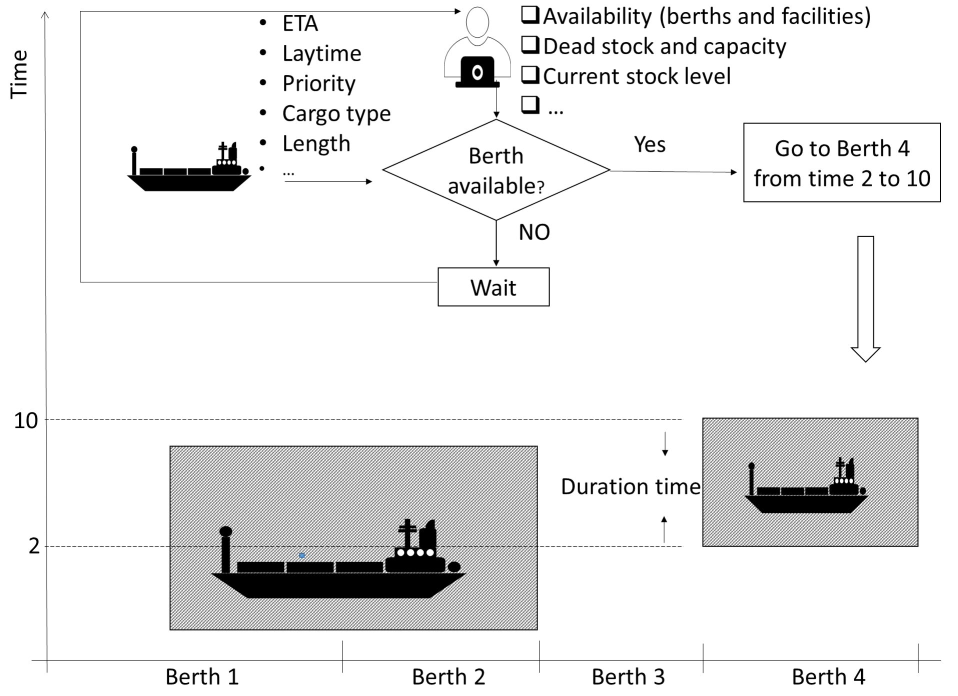


Figure 4.2: The berth allocation process in bulk terminals

(2) The unavailability time window of each berth is considered, which can be caused by weather conditions, maintenance requirements, or other stochastic factors.

(3) Each vessel has the earliest and the latest service time. This time window is related to the expected arrival time and the priority of the vessel.

(4) The stock level of each cargo type changes with the loading or discharging process, and the stock level of the corresponding cargo type should be within the range of deadstock and capacity.

4.3.2 Model

With the notation defined at Table 4.2, we propose the formulation of the hybrid BAP in bulk ports with unavailability and stock constraints, which specifically considers the situation of multiple cargo types on one vessel.

$$min \quad z = \sum_{i \in N} c_i (ct_i - t_i - g_i)^+ \tag{4.1}$$

Subject to:

$$\sum_{k \in M_i} x_{ik} = 1 + \sum_{k \in M \setminus \{|M|\}} z_{ik} \quad \forall i \in N \tag{4.2}$$

$$st_i \geq t_i \quad \forall i \in N \tag{4.3}$$

$$st_i \leq \gamma_{it} t + M(1 - \gamma_{it}) \quad \forall i \in N, t \in T \tag{4.4}$$

$$st_i + h_i \geq \gamma_{it}(t+1) \quad \forall i \in N, t \in T \tag{4.5}$$

$$\sum_{t \in T} \gamma_{it} \geq h_i \quad \forall i \in N \tag{4.6}$$

$$ct_i \geq st_i + h_i \quad \forall i \in N \tag{4.7}$$

$$\sum_{i \in N} st_j \geq ct_i - M(1 - y_{ijk}) \quad \forall i \in N, j \in N, i \neq j, k \in M \tag{4.8}$$

$$y_{ijk} + y_{jik} \leq 0.5(x_{ik} + x_{jk}) \quad \forall i \in N, j \in N, i \neq j, k \in M \tag{4.9}$$

$$y_{ijk} + y_{jik} \geq x_{ik} + x_{jk} - 1 \quad \forall i \in N, j \in N, i \neq j, k \in M \tag{4.10}$$

$$x_{ik} + x_{i,k+1} \geq 2 z_{ik} \quad \forall i \in N, k \in M \setminus \{|M|\} \tag{4.11}$$

$$\sum_{k \in M \setminus \{|M|\}} z_{ik} \leq 1 \quad \forall i \in N \tag{4.12}$$

$$l_i x_{ik} \leq \sum_{k \in M} L_k x_{ik} \quad \forall i \in N, k \in M \tag{4.13}$$

$$\sum_{\theta \in \Theta} \xi_{it}^{\theta} = \gamma_{it} \quad \forall i \in N, t \in T \tag{4.14}$$

$$\gamma_{i\theta} \sum_{t \in T} \xi_{it}^{\theta} \geq q_{i\theta} \quad \forall i \in N, \theta \in \Theta \tag{4.15}$$

Table 4.2: Notation of sets, parameters, and decision variables used in Chapter 4.

Notation	Explanation
Sets	
N	set of all vessels, $N = \{0, 1, \cdots, \lvert N\rvert\}$.
M	set of berths, $M = \{0, 1, \cdots, \lvert M\rvert\}$.
M_i	set of berths that can serve vessel i determined by cargo types.
T:	set of time periods, $T = \{0, 1, \cdots, \lvert T\rvert\}$.
Θ	set of product types, $\Theta = \{0, 1, \cdots, \lvert\Theta\rvert\}$.
Parameters	
l_i	the length of vessel i.
$r_{i\theta}$	rate of operation of vessel i on cargo type θ.
$q_{i\theta}$	quantity of cargoes on vessel i for cargo type θ.
t_i	expected arrival time of vessel i.
h_i	processing time of vessel i.
g_i	laytime of vessel i.
c_i	hourly demurrage cost of vessel i.
$[\alpha_i, \beta_i]$	start time window for vessel, i (α_i is related to arrival time of vessel, and β_i is related to priority and roud-trip duration).
$w_{l\theta}$	dead inventory level of cargo type θ.
$w_{h\theta}$	capacity of the inventory level of cargo type θ.
$w_{0\theta}$	current inventory level of cargo type θ at the start of planning horizon.
b_k	the position of berth k.
L_k	the maximum length of berth k.
$[s_k, e_k]$	berth k is available to serve vessels from time s_k to e_k.
Decision variables	
x_{ik}	equal to 1 if berth k is the start section of vessel i, and 0 otherwise.
y_{ijk}	equal to 1 if vessel i and vessel j are both assigned to berth k, and vessel i is processed before vessel j, and 0 otherwise
st_i	the starting time of vessel i
z_{ik}	equal to 1 if vessel i is berthed at k and $k+1$, and 0 otherwise, $k \in [0, 1, \ldots, \lvert M\rvert - 1]$
γ_{it}	equal to 1 if vessel i is berthed at time t, and 0 otherwise
ξ_{it}^{θ}	equal to 1 if cargo type θ of vessel i are operated at time t, and 0 otherwise

$$w_{l\theta} \leq w_{0\theta} + \sum_{i\in N}\sum_{m=0}^{m=t} \gamma_{i\theta}\xi_{it}^{\theta} \leq w_{h\theta} \quad \forall t \in T, \theta \in \Theta \tag{4.16}$$

$$x_{ik}s_k \leq st_i \leq x_{ik}(e_k - h_i) \quad \forall i \in N, k \in M \tag{4.17}$$

$$\alpha_i \leq st_i \leq \beta_i \quad \forall i \in N \tag{4.18}$$

$$x_{ik} \in \{0,1\} \quad \forall i \in N, k \in M \tag{4.19}$$

$$y_{ijk} \in \{0,1\} \quad \forall i \in N, j \in N, i \neq j, k \in M \tag{4.20}$$

$$\xi_{it}^{\theta} \in \{0,1\} \quad \forall i \in N, t \in T, \theta \in \Theta \tag{4.21}$$

$$z_{ik} \in \{0,1\} \quad \forall i \in N, k \in M \backslash \{|M|\} \tag{4.22}$$

$$\gamma_{it} \in \{0,1\} \quad \forall i \in N, t \in T \tag{4.23}$$

The objective function (4.1) is to minimize the demurrage fee of all vessels. Constraint (4.2) ensures each vessel i occupies at least one berth. Constraint (4.3)-(4.7) restrict the completion time and the start time of Vessel i. Constraints (4.8)-(4.10) are no overlapping restriction for vessels that be served at the same berth. Constraints (4.11)-(4.13) allow vessels to occupy two berths. Constraints (4.14)-(4.16) ensure that the current inventory during the loading or discharging of vessels can satisfy the requirement of stock of specific cargo type. Some practical factors which restrict the starting time and completion time of vessels are considered in this model. Constraint (4.17) represents the available time window of berths. Constraint (4.18) is the available time window of vessels. Constraints (4.19)-(4.23) specify the range of decision variables. The objective function (4.1) is nonlinear. Thus, they need to be linearized by defining an additional decision variable $\mu_i = (ct_i - t_i - g_i)^+$. The related additional constraints are defined as follows:

$$\mu_i \geq 0 \quad \forall i \in N \tag{4.24}$$

$$\mu_i \geq ct_i - ti - g_i \quad \forall i \in N \tag{4.25}$$

Therefore, the model can be reformulated as a mixed-integer linear program as follows:

$$min \quad z = \sum_{i\in N} c_i\mu_i \tag{4.26}$$

Subject to Constraints (4.2) - (4.25).

4.4 Numerical experiments

In this section, the MIP model proposed in Section 4.3.2 is tested using the CPLEX solver with the computational limit of 600s. All tests are running on an Intel Core i5 (1.7GHz) processor and use the version of CPLEX 12.8.0 under the C++ environment. We introduce the instance generation first and then analyze the model's performance under four different scenarios.

4.4.1 Generation of instances

We generate 12 instance sizes with different $|M|$ and $|N|$ as well as the consideration of unavailability and multiple cargo types within the time horizon of one week, as shown in Table 4.3. The unavailability can be incurred by maintenance requirements for facilities, extreme weather, or other unforeseen factors. The length of vessels and berths are generated following a uniform distribution of $[80,180]$ and $[120,160]$. The other detailed attributes related to the vessel are generated randomly, including arrival time, processing time, laytime, demurrage, night operation permission, and the cargo tonnage and type they carried.

Table 4.3: Information about the generated instances

Instance	$\|N\|$	$\|M\|$	Unavailability	Multiple cargo types
I1	6	3	No	Single
I2	6	3	Yes	Single
I3	12	3	No	Single
I4	12	3	Yes	Single
I5	18	3	No	Single
I6	18	3	Yes	Single
I7	6	5	No	Multiple
I8	6	5	Yes	Multiple
I9	12	5	No	Multiple
I10	12	5	Yes	Multiple
I11	18	5	No	Multiple
I12	18	5	Yes	Multiple

4.4.2 Results analysis and discussion

As highlighted in Section 4.2, the night berthing permission is considered in our model; thus, for those vessels that cannot be operated during the night (assumed from 1 am to 6 am), the following constraints (4.27) and (4.28) are added:

$$\begin{aligned} & st_i - \gamma_{iq} t - M(1-\gamma_{iq}) < 0 \\ & \forall i \in N, q \in [24p+1, 24p+5], p \in [0,31], t = 24p+1 \end{aligned} \tag{4.27}$$

$$\begin{aligned} & ct_i \geq \gamma_{iq} t \\ & \forall i \in N, q \in [24p+1, 24p+5], p \in [0,31], t = 24p+5 \end{aligned} \tag{4.28}$$

Table 4.4 shows the result of the expected demurrage fee and the computational time. The proposed MIP model can find the optimal solutions for all 12 instances by applying CPLEX, with up to 18 vessels and 5 berths. In Figure. 4.3, we compare the demurrage fee in four scenarios which differentiate in whether consider multiple cargo types and unavailability or not. We find that berths' unavailability can always significantly increase the demurrage fee, especially when the berths are busy. However, the multiple cargo types

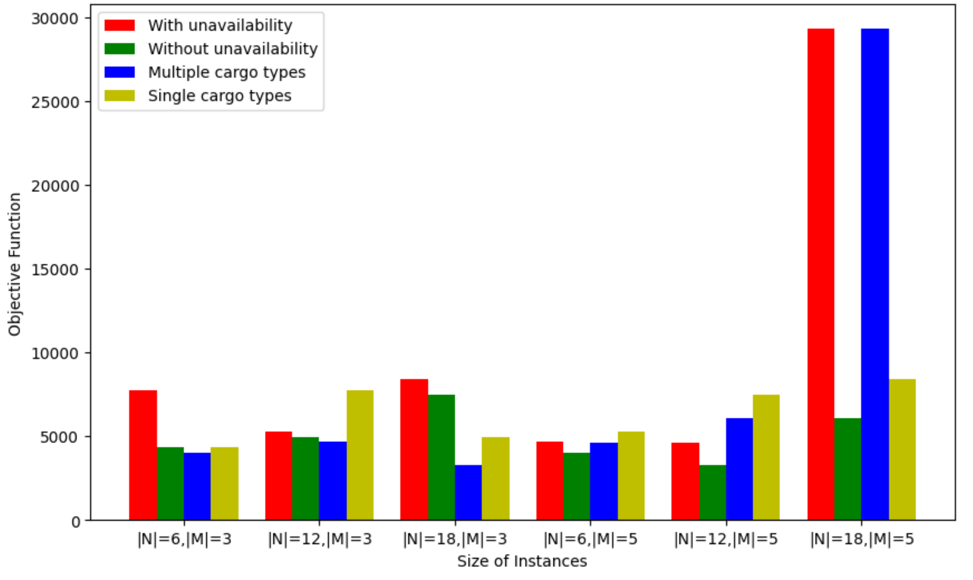


Figure 4.3: The comparison of demurrage fee under four different scenarios

on the same vessel have no significant impact when the port is idle, but it will obviously increase demurrage fees when the port is busy.

Table 4.4: Computational results for the proposed MIP model

Instance	Obj ($)	Time (s)	Instance	Obj ($)	Time (s)
I1	4347.00	1.64	I7	4036.50	2.28
I2	7762.50	1.27	I8	4657.50	0.80
I3	4968.00	11.36	I9	3283.15	2.50
I4	5267.00	19.17	I10	4621.50	4.89
I5	7464.00	179.38	I11	6110.00	24.34
I6	8393.50	240.02	I12	29330.00	306.67

4.4.3 Managerial insights and policy implications

This paper proposes a hybrid BAP model for bulk port managers to decide when and where to operate on the calling vessels considering the constraints of the unavailability of facilities and the stock level. With the experimental results in Section 4.4.2, the following implications are provided for the bulk port managers:

(1) In practice, unavailability of berths happens frequently, caused by many practical factors, such as extreme weather and facility maintenance. The BAP model, which ignores the unavailability, does not work in many practical applications and even makes the port into trouble. In addition, the unavailability of berths can significantly influence the berth allocation plan and further impact the total demurrage fee. Thus,

the bulk port managers should consider the unavailability when making decisions on berthing plans.

(2) Constraints (4.27) and (4.28) are for satisfying the requirement of individual vessels on night berthing permissions and thus improve the customer service level of the ports.

(3) Whether to consider stock level constraints largely depends on the actual situation of the ports. When the storage is approaching capacity, it is necessary to consider the stock level limitation in berth allocation. Otherwise, the vessel must wait until there is enough storage space, which can also make the ports into trouble.

4.5 Conclusions

Prior work on mathematical models and algorithms has solved the basic BAP in bulk ports. For instance, the author reports the specific features of berth operations in bulk ports that distinguish them from container ports [168]. However, these studies have either ignored some practical constraints (e.g., unavailability of berths and storage) or have not considered the multiple cargo types on one vessel, which can make it hard to apply those approaches under real-world conditions. In this chapter, we propose a hybrid BAP model for bulk ports with unavailability and stock level constraints, and we consider the case of multiple cargo types on one vessel specifically. We show the effectiveness of the proposed model by conducting numerical experiments on a set of distinct instances. The hybrid BAP extends earlier work of [172], providing a better fit for the loading or discharging operations in real-world bulk ports. The commercial software CPLEX can obtain optimal solutions with up to 18 vessels within 600 seconds. Most notably, this is the first study to our knowledge that dedicates itself to the BAP in bulk ports and considers unavailability and stock constraints simultaneously. Our solutions provide timely and effective decision support to port managers.

Chapters 3 and 4 address the research question **Q3**: “How does collaboration work as a means for efficient and resilient port operations?” from horizontal collaboration and vertical collaboration, respectively. Nonetheless, these collaborative planning models pre-assume the collaboration has already been established, disregarding the requirements and incentives of stakeholders. Thus, the establishment of an attractive and stable collaboration is studied in the next chapter.

Chapter 5

Collaborative Berth Allocation with Row-Generation Algorithms for Stable Cost Allocation

Chapter 5 answers the fourth research question (**Q4**): "How to generate attractive and stable collaboration?". We design novel and effective collaboration mechanisms among terminal operators that share the resources (berths and quay cranes). We first define the collaborative berth allocation problem and propose a mixed integer linear programming (MILP) model to minimize the total cost of all terminals, referred to as the coalitional costs. We adopt the core and the nucleolus concepts from cooperative game theory to allocate the coalitional costs such that stakeholders have stable incentives to collaborate. To obtain solutions for realistic instance sizes, we propose two exact row-generation-based core and nucleolus algorithms that are versatile and can be used for various combinatorial optimization problems.

The organization of this chapter is as follows. Section 5.1 introduces the research bacakground and Section 5.2 reviews the studies on collaborative berth allocation and articulates the research gap. Section 5.3 presents the MILP formulation of the HCBAP model and the related cooperative game. Section 5.4 describes the RG-based core algorithm and the nucleolus calculation mechanism for allocating the coalitional costs. Section 5.5 showcases the experimental results, and Section 5.6 offers a discussion and key insights. Finally, Section 5.7 provides conclusions.

This chapter has been submitted to a journal [25][1].

5.1 Introduction

Disruptions in global supply chain networks and crisis response policies such as the Covid-19 pandemic and the Red Sea crisis have recently highlighted the importance of container terminals as scarce resources in the networked global economy. The container crisis, in

[1]X. Lyu, E. Lalla-Ruiz, F. Schulte (2024), The collaborative berth allocation problem with row-generation algorithms for stable cost allocations.

particular, has demonstrated the need for enhanced resilient container terminal operations. On the other hand, advances in digital technology have stimulated collaborative planning through convenient information sharing in recent years. As a result, collaborative planning strategies, in which multiple stakeholders can provide service cooperatively based on resource sharing, are increasingly targeted by the industry to enhance performance in peak-demand situations and to compensate for temporarily limited capacity at certain nodes in the network. Through these strategies, economic, environmental, and intangible benefits can be obtained [10]. Accounting for over 90% of global trade, the maritime shipping industry has great opportunities and challenges to deal with when adopting this new trend of collaboration. Over the past two decades, compound annual growth in maritime trade has been 2.9% [1]. The increasing rate urges terminals to expand their capacity to ensure the efficiency of port service and enhance port resilience when facing enormous disruptions, such as the breakdowns of the COVID-19 pandemic. However, constructing the port and its supporting facilities requires substantial investments and would incur long-term influences on the environment. Consequently, Maersk and Hapag-Lloyd AG, as prominent companies with ownership of multiple terminals, have announced the new Gemini alliance aiming at extensive operational collaboration and an interconnected ocean network with industry-leading reliability [186].

Container terminals act as an essential intermediary hub for sailing voyages, and the efficiency of the port-of-call operations significantly impacts the smooth transport of cargo. Berth planning involves determining the berthing time and position for incoming vessels and is therefore one of the most critical decisions for terminal operators. Effective and efficient berth planning ensures the optimal utilization of available resources, minimizing vessel waiting times and increasing overall productivity. The classic Berth Allocation Problem (BAP) formalizes the decisions of when and where to discharge (or load) the incoming vessels. Figure 6.2 illustrates the BAP in a two-dimensional diagram. The two dimensions are the berthing line (the position that vessels can berth) and the timeline (the planning horizon), respectively. Each rectangle represents the berthing time and position allocated to each calling vessel. The work of [41] and [138] classifies the models and algorithms developed in BAP according to different features, while the general goal is to make the two-dimensional space occupied by as many rectangles as possible without overlapping and within the limits of capacity.

The Collaborative Berth Allocation Problem (CBAP) is more complex than that shown in Figure 6.2, as it deals with coordinating multiple parties; thus, new models are required to support decision-makers, especially from the operational level. Typically, two types of collaboration, vertical and horizontal, are recognized in the literature (as reviewed in Section 5.2). Partnerships in vertical collaboration are between different levels of the supply chain, while those in horizontal collaboration happen at the same level. Concerning vertical CBAP (VCBAP), collaborative berth allocation models considering the cooperative relationship between shipping lines and terminals are proposed by [37] and [38], that is, the terminal managers can take part in deciding the arrival time of vessels. The horizontal collaboration among terminal operators has also been studied as an effective strategy to improve port logistics efficiency [68]. In practice, HCBAP has not been adopted yet, because of commercial and regulation limitations. However, the requirement from the industry such as Gemini alliance [186], the horizontal CBAP (HCBAP) is crucial to achieving the collaboration because berths are important and scarce resources for terminals, while the relevant

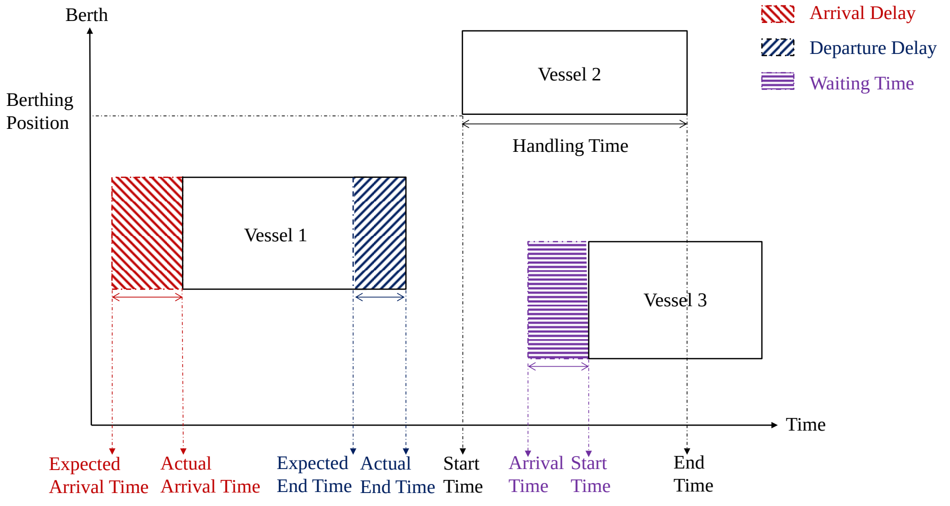


Figure 5.1: An illustration of the two-dimensional berthing plan.

studies are relatively limited. Only [96] and [22] formulate berth allocation models that allow one vessel to transfer to another terminal within the port based on sharing berths among terminals.

All the studies mentioned above assume that the collaboration has already formed. However, individual interests remain a primary concern for all stakeholders, and they may be reluctant to share their resources if they cannot obtain clear benefits. In this context, successful collaborative planning requires efficient shared-resource allocation methods to improve overall performance and appropriate incentives to convince individual participation, such as to steer effective collaborations [187]. Cooperative game theory provides theoretical approaches, such as the core and the nucleolus, to allocating the coalitional costs to individuals appropriately [21]. Specifically, the core ensures that collaborative members do not incur costs exceeding those associated with working independently, and the nucleolus aims to maximize the number of members within the collaboration. Notably, both methods require prior knowledge of costs associated with all potential coalitions. However, these methods tend to be computationally challenging in implementation because enumerating costs for all potential coalitions quickly becomes impossible when the coalitional costs are intertwined with (np-hard) combinatorial optimization problems, even with a limited number of participants. Thus, to overcome this limitation, we introduce two row-generation-based methods to calculate the core (subsequently referred to as the RG-based core) and the nucleolus mechanism to efficiently generate attractive cost allocations to individual members involved in the collaboration.

To sum up, this work proposes a collaborative berth allocation model in which multiple terminals within one port serve the calling vessels cooperatively. Besides, to facilitate successful collaborative berth allocation, we propose new optimization approaches building on two major concepts in cooperative game theory (i.e., the core and the nucleolus) to find attractive cost allocations, overcoming computational difficulties than simple enumeration-based methods, and thereby incentivizing individual terminals to form a coalition that they do not leave. The computational experiments show that the proposed model can result in significant cost savings for the entire coalition, while crucially maintaining stable collaboration incentives. Moreover, considering the realistic instance sizes, for instance, Hong Kong Port with five terminal operators [99] and Busan New Port with five terminal operators [76], the proposed cost allocation algorithms for calculating the core and the nucleolus can provide satisfying solutions for six collaborative terminals to ensure joining the collaboration is always attractive for individuals. In summary, we make in this chapter the following main contributions:

(1) We present a new mathematical model for collaborative bert allocation to minimize the entire cost of all terminals within one port by serving the calling vessels cooperatively, in which we consider the trade-off between the duration time of the vessel and the extra transhipment cost caused by the transfer of vessels.

(2) To ensure stable collaboration incentives, we develop a row generation algorithm to obtain the core solution of cost allocation based on cooperative game theory. The idea is to make it clear to individuals how much they stand to gain to avoid some players benefiting greatly while some even not, thereby maintaining a stable collaboration.

(3) We further strengthen collaboration stability based on the core solutions by suggesting a novel mechanism to find the nucleolus solution for cost allocations of the collaborative berth allocation problem.

(4) With the proposed row-generation-based core algorithm and nucleolus mechanism, we provide general-purpose approaches to achieve attractive and stable cost (or profits) allocations for collaborative combinatorial optimization problems. To the best of our knowledge, the proposed row-generation approach for the nucleolus is the first of its kind for combinatorial optimization problems.

5.2 Literature review

In this section, we present an extensive review of collaborative berth allocation. First, we describe two typical types of collaboration in BAP: vertical collaboration between the shipping line and the terminal in Section 5.2.1 and horizontal collaboration among multiple terminals in Section 5.2.2. Our focus is the mathematical model that can support terminal operators in making berth allocation decisions; therefore, we also categorize integrated problems with berth allocation as BAP. In Section 5.2.3, we cover the application of cooperative game theory to collaborative planning in maritime shipping and identify the research gap explicitly in Section 5.2.4.

5.2.1 BAP with vertical collaboration

For vertical collaboration, the berthing plan is often organized based on the interaction between the shipping company and the terminal manager. For example, the shipping company can slow down their sailing speed according to the busyness level of the terminal, thereby alleviating terminal congestion and reducing unnecessary fuel costs. The terminal operators can participate in adjusting the arrival time of vessels, which distinguishes VCBAP from the traditional BAP significantly, and terminal resources restrict the duration time of the vessel. Therefore, coordinating the sailing voyage and terminal operation is critical for VCBAP.

Although the concept of collaboration is not explicitly proposed, vessels' arrival time is firstly regarded as a decision variable in the BAP model proposed by [188]. They aim to reduce fuel costs by minimizing the waiting time of vessels at the terminal. However, it is only partially reasonable since the fuel consumption during the sailing voyage is more prominent than that of mooring periods at the quayside [189]. Therefore, a more elaborate BAP model considering the fuel consumption in both sailing and mooring periods is proposed by [190]. Furthermore, they transform the nonlinear model into a mixed integer second-order cone programming model to overcome the problem-solving complexity. The work of [191] compares the cost of different berthing plans by simulating different scenarios of vessel arrival time. Their experiment results show that the flexible arrival time suggested by the terminal performs better than treating it as a previously-known parameter in terms of terminals' operational efficiency and shipping lines' fuel consumption. A discrete event simulation model that integrates speed optimization with BAP is developed by [192], demonstrating significant benefits of reductions in fuel consumption and dwell time. Besides, there are also some innovative considerations in the literature: incorporating the utility conception of shipping lines in the model, where a higher bunker and inventory cost decreases the utility [31] and emphasizing vessel service differentiation and develops a bi-objective model for the integrated collaborative berth allocation and quay crane assignment problem [193].

It is worth noting that all the above studies focused on a single terminal. Only two papers consider the multi-port setting. In the work of [38], they propose a multi-port berth allocation problem, in which shipping lines and multiple ports decide the berthing position and berthing time for each vessel at each port coordinately. They aim to minimize the total fuel consumption of the shipping line and the operation cost of terminals along the entire shipping route. The proposed MIP model performs well for small-scale instances but needs to improve when the size increases. Then, an exact algorithm based on branch-and-cut-and-price procedures to solve the instances reflecting the real-world scenarios is proposed in [94].

5.2.2 BAP with horizontal collaboration

In horizontal collaboration, different terminals can work together to provide the discharging (or loading) service, potentially sharing the information of the calling vessels and facilities to fully use terminal resources [115]. However, some of these terminals are competitors and may not be willing to collaborate. In this regard, on top of an efficient berth allocation plan, it is essential to convince terminals about collaborating as more benefits can be obtained.

There have been studies demonstrating the benefits of consolidating container terminals. Study of [67] proposes a conceptual framework of a collaborative operational system among terminals. The results show that terminal collaboration can reduce vessels' waiting time, balance resource utilization, and increase overall profits. The coalitions forming by different combinations among three terminals at Karachi Port are investigated by [69], which models a Bertrand game with one outside competitor, the coalition, and the terminal in Karachi Port (if any) that has not joined the coalition. Empirical research on facilitating terminal coalition at the Hong Kong Port is conducted by [75], consisting of five terminal operators. The work of [76] simulates the effects of sharing berth resources among terminals within one port using scenario analysis. Forming terminal coalition is classified by [74] as intra-port collaboration, and they develop quantitative tools to analyze the dynamics of individual profit of terminal operators and their willingness to cooperate. The authors pre-assume two cooperation schemes and seven transfer fee policies and then investigate the changes in profits before and after collaboration.

However, limited studies contribute to the HCBAP model in forming terminal coalitions. First studies by [96] and [97] address a variation of BAP at multi-user terminals, which assign vessels that would usually be served at the terminal to an external terminal due to waiting time limitations. Nevertheless, these models tacitly assume that the cooperative alliance is already formed and, thus, ignore the rational decisions of individual terminals as a requisite to form such alliances.

5.2.3 Cooperative game theory models

In real cases, terminal operators pursue enhancing their own interests [115]. Thus, convincing individual terminals to collaborate and abide by the coalitional decisions is a significant concern. Cooperative game theory has been increasingly applied in collaborative maritime shipping in recent decades [125]. Their focus is generally on allocating the coalitional benefits appropriately to incentivize individual players to stay in the collaboration [194], thereby maintaining collaboration stability. The core for collaboration stability and the nucleolus for enhancing stability [122] are applied in collaborative transportation problems. However, their computational time grows exponentially with the increased number of players; thus, they fail to deal with realistic problems.

For the CBAP, most researchers only consider minimizing the overall cost; however, studies covering rational individual considerations are limited. The collaborative mechanism for berth allocation proposed by [31] implies the cooperative and competitive relationship between the terminal and the shipping line to ensure that the berthing plan is mutually beneficial to both parties. Game theory is embedded in heuristics of [195] for solving the BAP, and [69] design a two-stage Bertrand non-cooperative game for terminals within one port. [94] design a cooperative game consisting of the shipping line and the terminal. They apply the Shapley Value Method (SVM) and Equal Profit Method (EPM) to allocate the joint cost among the individual member fairly. Similarly, SVM and the core are applied in [196] to allocate the total cost of each group and select the stable groups. Based on the previous results, they propose a new integer programming model to determine the collaborative groups with the maximum revenue. However, in dealing with the cooperative part, the study depends on the enumeration method, which greatly limits the number of partners joining the game.

5.2.4 Overview and research gap

According to the classification scheme in [41], we use three attributes to describe the problem properties of the CBAP model. The spatial attribute reflects the quay layout in discrete (DS) or continuous (CN) berths. The handling time attribute concerns the way of dealing with vessel handling time in the model: fixed (FX), quay crane dependent (QD), and

Table 5.1: Overview of the CBAP model in the literature.

Type	Reference	Problem Properties			Solution Method	Stability Consideration
		Spatial Attribute	Handling Attribute	Performance Measure		
Vertical Collaboration	[188]	DS	FX	$\Sigma(wait + tard)$	H	
	[191]	DS	QD	$\Sigma(fuel + tard + extra)$	SM	
	[190]	CN	FX	$\Sigma(tard + wait + fuel)$	MIP	
	[31]	DS	FX	$\Sigma(utility - extra)$	MIP	✓
	[38]	DS	PD	$\Sigma(wait + hand + tard + fuel)$	MIP	
	[193]	CN	QD	$\Sigma(tard + wait + fuel)$	MIP	
	[94]	DS	PD	$\Sigma(wait + hand + tard + fuel)$	B&P, CG	✓
Horizontal Collaboration	[96]	DS	PD	$\Sigma(wait + hand + tard + fuel)$	H	
	[69]	-	-	$\Sigma(utility)$	LM	✓
	[134]	-	FX	$\Sigma(hand + extra)$	H	
	[197]	CN	QD	$\Sigma(hand + extra)$	MIP	
	[198]	DS	FX	$\Sigma(hand + tard + extra)$	H	
	[99]	DS	FX	$\Sigma(hand + tard + extra)$	SM	
	[97]	CN	QD	$\Sigma(hand + tard + extra)$	H	
	[74]	-	QD	$\Sigma(utility)$	SM	✓
	[135]	CN	PD	$\Sigma(tard + extra)$	LR	
	[25]	DS	QD	$\Sigma(hand + wait + tard + extra)$	MIP, CG	✓

Note: LR, lagrange relaxation; B&P, branch and price; SM, simulation; H, heuristics; CG, cooperative game theory.

position dependent (PD). The performance measure attribute lists six different evaluation criteria: the waiting time of vessels (wait), handling time of vessels (hand), departure tardiness of vessels (tard), extra container transshipment cost (extra), fuel consumption (fuel), and utility calculation of terminals (utility).

The relevant CBAP literature is exhibited in Table 5.1, sorted by collaboration types, problem properties, solution methods, and whether considering collaboration stability. The last row highlights our research. From it, we can observe that although the concept of collaborative berth planning has been recognized over the last decade, the matching planning models are still in their infancy. Especially for horizontal collaboration among multiple terminals, most studies only analyze the potential advantages, while few can support making decisions on berth allocation from the operational level. Furthermore, effective cost allocation models to allocate the coalitional benefits for maintaining collaboration stability are still lacking. Thus, other than developing an instructive CBAP model from the operational planning perspective, we further present supportive cost allocation methods that are vital to enable a stable collaboration in practice. This paper aims to provide decision-support tools for practitioners in maritime shipping to facilitate collaborative berth allocation effectively.

5.3 Collaborative berth allocation problem as a cooperative game

The proposed HCBAP model described in Section 5.3.1 and Section 5.3.2 is based on the discrete and dynamic BAP, in which multiple terminals serve the calling vessels cooperatively by sharing the berths and quay cranes. This model strongly depends on the collaboration among terminals; therefore, the benefits of such collaboration need to be explicit to convince individual terminals to join the coalition. Thus, we further define a cooperative game in Section 5.3.3 using the objective value of the HCBAP model as the characteristic function.

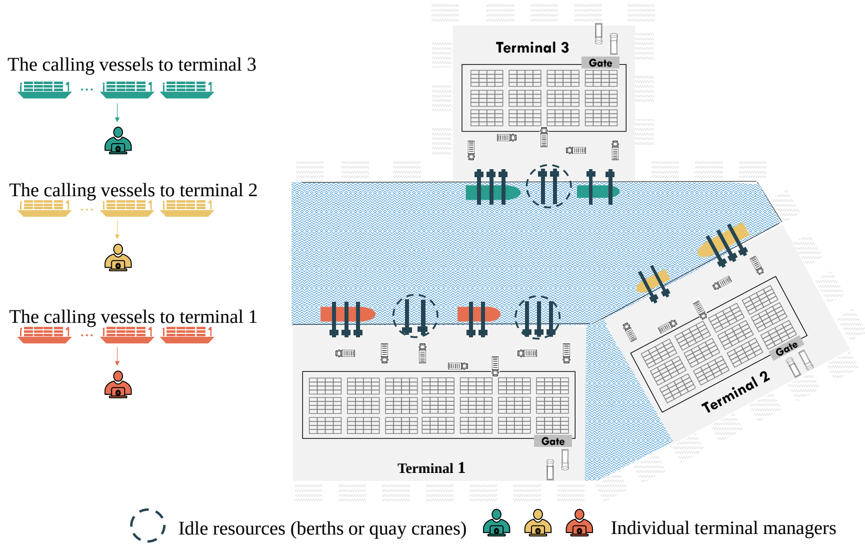


Figure 5.2: Berthing plan without collaboration.

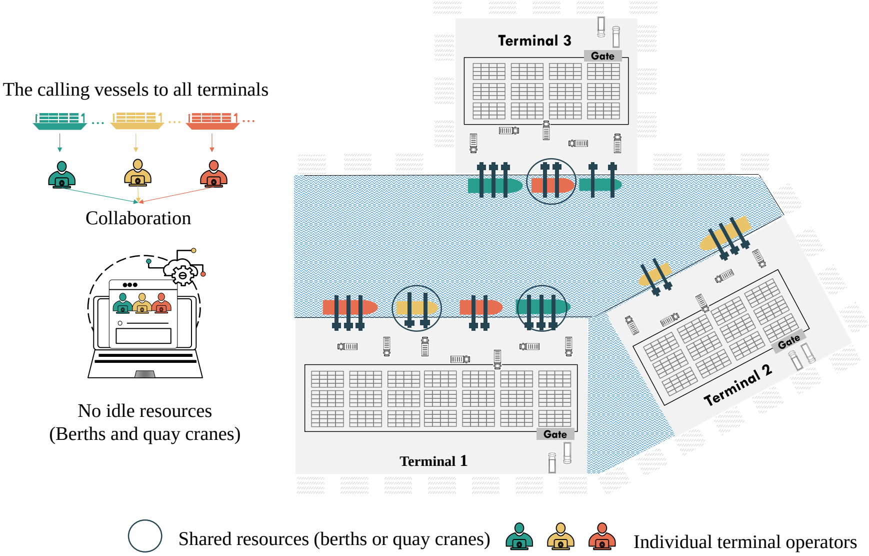


Figure 5.3: Berthing plan with collaboration.

5.3.1 Problem description of HCBAP

A calling vessel can be regarded as the terminal's customer. The terminal earns money by providing discharging (or loading) services for its customers. Delay in this service directly damages customer satisfaction which will influence the development of the terminal in the long term. Without collaboration, the vessels can only wait at their contracted terminals until the berths and quay cranes are available. With collaboration among terminals, the vessels can be berthed at other terminals providing better time slots while incurring extra container transshipment costs. Thus, terminal operators need to balance the service quality and service cost during the planning. Our HCBAP model incorporates a trade-off between extra container transshipment costs caused by vessel transfer between terminals and the cost of vessel tardiness. We assume a coalition of terminals is willing to share the resources (e.g., berths and relevant information about the incoming vessels) with other terminals within the port. If the contracted terminal cannot serve the calling vessel because of disruptive events or if providing the service is economically unreasonable, these vessels are allowed to transfer to another terminal in the coalition for loading or discharging, and the saving costs are shared.

Figures 5.2 and 5.3 illustrate the berthing plan without and with the collaboration based on an example port with three terminals. In Figure 5.2, terminal operators independently make their own planning on berth allocation for their respective vessels. That is, each terminal's berth planning is limited by its internally accessible berth and quay crane resources. While in the collaborative case shown in Figure 5.3, the calling vessel can berth at any terminal of the coalition given that the necessary berth resources are available. In practice, the yard location of containers loaded to (or discharged from) the calling vessel has been decided before. Therefore, extra container transshipment fees due to vessel transfer between terminals have to be considered in the cost calculation. In this way, the proposed HCBAP model achieves a simultaneous berthing plan for multiple terminals within a port.

Above all, we conclude our problem as a collaborative berth allocation problem based on horizontal collaboration among terminals within one port. We frame the problem as concentrating all the vessel's calling information and making the berthing plan optimally, considering the available resources of all collaborative terminals and providing decision support for both cases with and without disruptions. Specifically, we only consider the quayside operation, and the inland schedule of container transportation is out of our scope. Thus, we assume all the related containers have already arrived at the terminal, waiting for the loading or unloading operations.

5.3.2 HCBAP model formulation

This section first introduces assumptions of our HCBAP model as follows:

(1) Berth positions are discrete and one vessel can only occupy one berth position.

(2) The loading/discharging operation by quay cranes for each vessel is assumed to be conducted continuously without interruption.

Next, we develop a mixed-integer linear programming (MILP) model for the proposed collaborative berth allocation problem with horizontal collaboration among terminal operators. The objective is to minimize the total service costs of all terminals. The model outputs

Table 5.2: Notation of sets, parameters, and decision variables used in Chapter 5.

Notation	Explanation
Sets	
V	set of all vessels.
T	set of one-hour time periods.
M	set of all terminals within the port.
B_m	set of berths at terminal $m \in M$.
Parameters	
c^{ι}_{im}	unit cost of inter-terminal container transshipment for vessel $i \in V$ from its contracted terminal to terminal $m \in M$, given in units of USD per TEU.
c^{ω}_{i}	penalty rate of vessel $i \in V$ for waiting service given in units of USD per hour.
c^{δ}_{i}	penalty rate of vessel $i \in V$ for departure tardiness given in units of USD per hour.
c^{κ}	operation cost rate given in units of USD per Quay Crane(QC)-hour.
a_i	expected arrival time of vessel $i \in V$.
d_i	expected departure time of vessel $i \in V$.
w_i	requirement for QC-hour of vessel $i \in V$.
g_i	the number of container units (TEU) required to be loaded or discharged on vessel $i \in v$.
Q_m	the total number of available quay cranes at terminal $m \in M$.
Decision variables	
z	the total cost for serving all calling vessels.
s_i	starting time of vessel $i \in V$.
e_i	ending time of vessel $i \in V$.
x_{im}	binary variables equal to 1 if vessel $i \in V$ is berthed at terminal $m \in M$, and 0 otherwise.
$\bar{x}_{imk}$	binary variables equal to 1 if vessel $i \in V$ is berthed at berth $k \in B_m$ of terminal $m \in M$, and 0 otherwise.
y_{ijmk}	binary variables equal to 1 if vessel $i \in V$ and vessel $j \in V$ are both assigned to berth $k \in B_m$ of terminal $m \in M$ and vessel $i \in V$ is processed before vessel $j \in V$, and 0 otherwise.
q_{imt}	the number of quay cranes assigned to vessel $i \in V$ when time $t \in T$ at terminal $m \in M$.
r_{it}	binary variables equal to 1 if vessel $i \in V$ is operated when time $t \in T$, and 0 otherwise.
γ_{imt}	binary variables equal to 1 if vessel $i \in V$ is operated when time $t \in T$ at terminal $m \in M$, and 0 otherwise.

(i) which berth at which terminal the vessel is served, (ii) the vessels' berthing time, (iii) the number of quay cranes operating within the service time, and (iv) the departure time. We list the used notations in Table 5.2. Based on the notations, the proposed HCBAP model is formulated as follows:

$$\min \quad z = \sum_{i\in V}\sum_{m\in M} c^{\iota}_{im} g_i x_{im} + \sum_{i\in V} c^{\omega}_i (s_i - a_i) + \sum_{i\in V} c^{\delta}_i (e_i - d_i)^+ + \sum_{i\in V}\sum_{m\in M}\sum_{t\in T} c^{\kappa} q_{imt} \tag{5.1}$$

Subject to:

$$\sum_{m\in M} x_{im} = 1 \quad \forall i \in V \tag{5.2}$$

$$\sum_{m\in M}\sum_{k\in B_m} \bar{x}_{imk} = 1 \quad \forall i \in V \tag{5.3}$$

$$s_i \le t\gamma_{it} + M(1 - r_{it}) \quad \forall i \in V, t \in T \tag{5.4}$$

$$e_i \ge (t+1) r_{it} \quad \forall i \in V, t \in T \tag{5.5}$$

$$\sum_{t\in T} r_{it} = e_i - s_i \quad \forall i \in V \tag{5.6}$$

$$\sum_{t\in T} q_{imt} \ge w_i x_{im} \quad \forall i \in V, m \in M \tag{5.7}$$

$$\sum_{i\in V} q_{imt} \le Q_m \quad \forall t \in T, m \in M \tag{5.8}$$

$$M(\gamma_{imt} - 1) - q_{imt} \le 0 \quad \forall i \in V, m \in M, t \in T, \tag{5.9}$$

$$q_{imt} \le M\gamma_{imt} \quad \forall i \in V, m \in M, t \in T \tag{5.10}$$

$$\sum_{m\in M} \gamma_{imt} = r_{it} \quad \forall i \in V, t \in T \tag{5.11}$$

$$\sum_{k\in B_m} \bar{x}_{imk} = x_{im} \quad \forall i \in V, m \in M \tag{5.12}$$

$$s_j \ge e_i - M(1 - y_{ijmk}) \quad \forall i \in V, j \in V, i \ne j, m \in M, k \in B_m \tag{5.13}$$

$$y_{ijmk} + y_{jimk} \le 0.5(\bar{x}_{imk} + \bar{x}_{jmk}) \quad \forall i \in V, j \in V, i \ne j, m \in M, k \in B_m \tag{5.14}$$

$$y_{ijmk} + y_{jimk} \ge \bar{x}_{imk} + \bar{x}_{jmk} - 1 \quad \forall i \in V, j \in V, i \ne j, m \in M, k \in B_m \tag{5.15}$$

$$s_i, e_i \in \{a_i, ..., |T|\} \quad \forall i \in V \tag{5.16}$$

$$x_{im}, \bar{x}_{imk}, r_{it}, \gamma_{imt} \in \{0,1\} \quad \forall i \in V, m \in M, t \in T, k \in B_m \tag{5.17}$$

$$y_{ijmk} \in \{0,1\} \quad \forall i \in V, j \in V, i \ne j, m \in M, k \in B_m \tag{5.18}$$

The objective function (5.1) minimizes the total service costs z of all terminals, consisting of four parts. The first part is the cost caused by extra container transshipment between terminals, defined as inter-terminal transportation (ITT) by [61]. The parameter c^{ι}_{im} indicates the unit cost of moving one container from the contracted terminal of vessel i to another terminal m, which is estimated based on the fuel costs of container moving among terminals according to formulation (5.19). In detail, l_{im} represents the distance between two terminals. Parameter α is the fuel cost of unit distance, and β is the number of containers that can be transported at one time. The second part is the penalty cost for waiting after the vessel arrives at the port. The third part is the penalty cost for the tardiness of vessels' departure time. The fourth part is the operation cost of quay cranes.

$$c_{im}^{\iota} = \frac{\alpha l_{im}}{\beta} \tag{5.19}$$

Constraint (5.2) ensures that each vessel is operated at only one terminal. Constraint (5.3) ensures that each vessel is operated at only one berth of one terminal. Constraints (5.4)-(5.6) determine the service starting time and ending time for vessels. Constraint (5.7) enforces that the total number of assigned quay cranes must satisfy the vessel's requirement. Constraint (5.8) ensures that the number of quay cranes operating simultaneously cannot exceed the maximum number available at the terminal. Constraints (5.9)-(5.10) denote the relationship of variables r_{imt} and q_{imt}, implicating that no quay crane is assigned when the vessel is not berthed. The consistent setting of the corresponding variables related to berthing position ($\bar{x}_{imk}$ and x_{im}) and handling time (γ_{imt} and r_{it}) is incorporated in Constraints (5.11)-(5.12). Constraints (5.13)-(5.15) ensure no overlapping exists for vessels that are served at the same berth of the same terminal. Constraint (5.16) restricts the service starting time to be after the vessel's arrival and the service ending time to be within the planning horizon. Constraints (5.17)-(5.18) define the remaining decision variables.

The third part of the objective function is nonlinear, and we linearize the objective function by defining an auxiliary variable $\mu_i = (e_i - d_i)^+$. Additional constraints (5.20) and (5.21) are added for restricting μ_i.

$$\mu_i \geq 0 \quad \forall i \in V \tag{5.20}$$

$$\mu_i \geq e_i - d_i \quad \forall i \in V \tag{5.21}$$

Therefore, we reformulate the model as follows:

$$\min \quad z = \sum_{i \in V} \sum_{m \in M} c_{im}^{\iota} g_i x_{im} + \sum_{i \in V} c_i^{\omega}(s_i - a_i) + \sum_{i \in V} c_i^{\delta} \mu_i + \sum_{i \in V} \sum_{m \in M} \sum_{t \in T} c^{\kappa} q_{imt} \tag{5.22}$$

Subject to Constraints (5.2)-(5.21).

5.3.3 Cooperative berth allocation game

Our cooperative game is based on the HCBAP model, in which a set of terminal operators $M = \{1, 2, \dots\}$ participate as players, and $\mathcal{N}$ is the set of all non-empty subsets of M. Each element in $\mathcal{N}$ represents one possible terminal coalition S. In other words, each S is actually a set of some terminal operators, and there are $2^{|M|} - 1$ different S, that is, $\mathcal{N} = \{S_1, S_2, ..., S_{2^{|M|}-1}\}$. For simplicity, we just use S in the following sections. As stated above, $S \subseteq M$ and $S \in \mathcal{N}$. Specifically, the coalition formed by all players is called the *grand coalition*. The *characteristic function* $C(S)$ represents the impact of a coalition S in the cooperative game theory, which in this case is defined as the objective value of the HCBAP model. For the cost of players who make decisions independently without collaboration, we call it *stand-alone* cost.

The characteristic function satisfies the following two conditions required in cooperative game theory:

$$C(\emptyset) = 0 \tag{5.23}$$

$$C(S) + C(T) \geq C(S \cup T) \quad \forall S, T \subseteq M, S \cap T = \emptyset \tag{5.24}$$

Equation (5.23) states that there is no cost in an empty coalition. Equation (5.24), referred to as *subaddivity*, ensures that forming a coalition can always generate no more cost than when operating independently. Furthermore, a cost allocation vector $\boldsymbol{f} = \{f_1, f_2, ..., f_n\}$ denotes the cost allocated to each player. Subsequently, two properties *efficiency* and *individual rationality* are defined in equations (5.25) and (5.26), respectively. Efficiency means all costs in the coalition are distributed to individuals, and individual rationality states that the cost allocated to each individual cannot exceed its stand-alone cost.

$$\sum_{m \in M} f_m = C(M) \tag{5.25}$$

$$f_m \leq C(\{m\}) \quad \forall m \in M \tag{5.26}$$

5.4 Cost allocation algorithms for stable and attractive collaboration

The HCBAP model proposed in Section 5.3.2 supports the centralized system in which multiple terminals are involved to cooperate on berth allocation planning for the calling vessels. Essentially, it aims to minimize the overall cost based on the assumption that the collaboration has already formed. However, a genuine concern for individual terminals is whether staying in the coalition is in their best interest; if not, they may choose to form a sub-coalition or work independently without collaboration. Thus, a reasonable cost allocation strategy to convince individual terminals is crucial for a stable collaboration in practice. In this regard, we adopt the core and the nucleolus concepts from cooperative game theory to allocate the coalitional costs among collaborative terminals. In detail, the core can guarantee that no collaborative terminals cost more than working alone, and the nucleolus aims to allow as many terminals to save costs within the collaboration as possible, while both methods require the costs of all potential coalitions to be pre-known. That is to say, the calculation of the core and the nucleolus needs multiple iterations of the MILP model to obtain the costs for all possible coalitions as inputs. Due to the NP-hard nature of the optimization problem which is already difficult to solve in a one-player setting. If we want to obtain Core and Nucleolus solutions, we need to solve this problem for every subset of players, that is, up to $2^6 - 1$ (null player coalition) or 63 times. To address this challenge, we develop two efficient algorithms based on the two essential concepts in cooperative game theory: the core in Section 5.4.1 and the nucleolus in Section 5.4.2, combing with the combinatorial optimization model of HCBAP, to allocate the coalitional costs while keeping the stability of collaboration. Finally, we give an example as an illustration of the proposed RG-based core and the nucleolus mechanism in Section 5.4.3.

5.4.1 Cost allocation in the core

The core is one of the most widespread concepts for stable collaboration in cooperative game theory. Let us denote the cost allocation vector $\boldsymbol{f}(S) = \sum_{j \in S} f_j$. Given the total cost $C(M)$, a solution consisting of the cost distribution over all players and satisfying the condition of the core is referred to as *imputation*. In addition to efficiency, it requires no sub-coalition to incentivize individual players to leave the grand coalition. Therefore, we formulate the core solution of our cost allocation problem in equation (5.27). As a result of the equation, the number of constraints denoted in the core grows exponentially to $2^{|M|} - 1$, making the model difficult to solve. To cope with that, we develop a row generation method based on the one proposed by [199] that enables tackling such a computational shortcoming. In doing so, we first formulate the master problem (**MP**) and the subproblem (**SP**), then we introduce the procedure of the RG-based core algorithm.

$$\text{Core}(M, \boldsymbol{f}) = \left\{ f \in \mathbb{R} | \sum_{m \in M} f_m = C(M), \text{and} \sum_{m \in S} f_m \leq C(S) \quad \forall S \subset M, S \neq \emptyset \right\} \tag{5.27}$$

MP model

The difficulty of calculating the core directly by Equation (5.27) is that each possible terminal coalition S will add one more constraint and the core solution needs to satisfy all the constraints. Thus, the master problem of the row generation approach is to calculate the cost allocation with some limited constraints. The current result of the master problem then assists in finding more constraints in the subproblem.

As stated already, in order to calculate the cost allocation based on a limited number of constraints, we define the following parameter Θ and decision variables in the master problem:

Parameter:

- Θ: the set of potential coalition S, initialized as $\Theta = \{\{1\}, \{2\}, ..., \{n\}\}$

Decision variables:

- δ: the minimum cost savings considering all the coalition S in current Θ.
- f_m: the cost allocated to player m.

Then, we formulate the **MP** model of our RG-based core algorithm as follows:

$$\min \quad \delta \tag{5.28}$$

Subject to:

$$\sum_{m \in S} f_m - \delta \leq C(S) \quad \forall S \in \Theta \tag{5.29}$$

$$\sum_{m \in M} f_m = C(M) \tag{5.30}$$

$$f_m \in \mathbb{R}, \forall m \in M \tag{5.31}$$

$$\delta \geq 0 \tag{5.32}$$

The value of the objective function (5.28) indicates whether the core is empty. If $\delta = 0$, then the core of the problem is not empty, and the value of f_m is the cost allocation in the core. In contrast, if $\delta > 0$, the problem has an empty core, which means the grand coalition is unstable regardless of the cost allocation solution. Constraints (5.29)-(5.30) embody the core definition. Constraints(5.31)-(5.32) define the decision variables.

SP model

To search for the sub-coalition $S^{'}$ that violates the core definition the most, the following decision variable ξ_m and parameter ζ_{im} need to be further defined in the subproblem.

Parameters:

- ζ_{im}: binary parameters equal to 1 if vessel $i \in V$ is the contracted customer of terminal m, and 0 otherwise.
- $\widehat{f_m}$: stand-alone costs of terminal m without any collaboration with other terminals.

Decision variables:

- ξ_m: binary variables equal to 1 if terminal m belongs to the coalition $S^{'}$, and 0 otherwise.

Continuing the notion used in Section 5.3.2, the **SP** model is given as:

$$\max \quad \sum_{m \in M} f_m \xi_m - \left[Obj - \sum_{m \in M} \widehat{f_m}(1 - \xi_m) \right] \tag{5.33}$$

$$Obj = z \tag{5.34}$$

$$x_{im} \geq \zeta_{im}(1 - \xi_m) \quad \forall i \in V, m \in M \tag{5.35}$$

$$x_{im} \leq \zeta_{im} + \xi_m \quad \forall i \in V, m \in M \tag{5.36}$$

and constraints (5.2) - (5.21).

The objective function (5.33) outputs the sub-coalition $S^{'} \notin \Theta$ that violates the core condition most. Constraints (5.35) and (5.36) state the relationship of the definition of ζ_{im} and ξ_m, restricting terminal $m \notin S^{'}$ can only serve its own customer vessels.

RG-based core algorithm

Algorithm 2 describes procedures of the proposed RG-based core algorithm.

The set of all possible coalitions, Θ, is initialized $\Theta = \{\{1\},\{2\},...,\{n\}\}$ in line 1. Starting from Θ, we run the **MP** model to obtain the value δ and f_m for $m \in M$. If $\delta > 0$, the problem has an empty core, and the algorithm stops. Otherwise, if $\delta = 0$, the **SP** model aims to find a sub-coalition $S^{'} \notin \Theta$ that maximizes $\sum_{m \in S^{'}} f_m - C(S^{'})$. It aims to search for the coalition $S^{'}$ that violates the core definition most. If $S^{'}$ exists, update $\Theta = \Theta \cup \{S^{'}\}$, and return to line 2; otherwise, the current vector $\boldsymbol{f}$ is cost allocation in the core.

Algorithm 2: Algorithm for Calculating the Core based on Row Generation Method

```
1  Initialization: Θ = {{1},{2},...,{n}}
2  Run model MP, obtain the value δ and f_m for m ∈ M
3  if δ > 0 then
4  |   Stop, and the problem has an empty core
5  else
6  |   Run model SP to find a sub-coalition S' = argmax_{S'∉Θ} ( Σ_{m∈S'} f_m − C(S') )
7  |   if S' exists then
8  |   |   Θ = Θ ∪ {S'}
9  |   |   Return to line 2
10 |   else
11 |   |   Current f_m for m ∈ M are in the core
   Output: One core solution f
```

5.4.2 Cost allocation in the nucleolus

The core solution can provide stable outcomes for cost allocation. However, it is not necessarily unique, and different cost allocations can be in the core [122, 200]. In such cases, decision-makers require additional support to select one among them. Therefore, the problem of choosing a cost allocation in the core is raised. In this regard, the nucleolus, introduced by [201], is another well-known allocation rule in cooperative game theory. It is considered the "most stable" cost allocation in the sense that it lexicographically minimizes dissatisfaction among all possible coalitions [202]. Additionally, the nucleolus is unique and lies in the core (if not empty), making it an attractive and preferred choice over other shared cost allocation methods for decision-makers in the collaboration [203]. However, calculating the nucleolus can be challenging when the number of players increases, especially when it intertwines with solving combinatorial optimization problems. Despite these challenges, the nucleolus provides more substantial support for decision-makers on cost allocation than the core solution due to its superior stability properties and unique nature. Therefore, we propose an effective mechanism to compute the nucleolus for the collaborative berth allocation game.

To illustrate the above, we first give the definition of nucleolus from a mathematical view and then describe the **tight sets** and **balancedness** proposed by [**?**]. Next, we present the general framework for finding the nucleolus. Then, we detail the designed verifying and updating algorithms, respectively.

- **Definition of the Nucleolus:** We denote the excess of a coalition S as $e(S,\boldsymbol{f}) := C(S) - \sum_{m\in S} f_m = C(S) - \boldsymbol{f}(S)$, where the cost allocation vector is denoted by $\boldsymbol{f}$. It reflects how satisfied the players in coalition S are with the corresponding cost allocation in vector $\boldsymbol{f}$. For any $\boldsymbol{f}$, let $\Upsilon(\boldsymbol{f}) = \big(e(\boldsymbol{f},S_1),\dots,e(\boldsymbol{f},S_{2^n-2})\big)$ be excess values of 2^n-2 coalitions with respect to cost allocation $\boldsymbol{f}$ that are stored in a none-decreasing order, n is the number of players in the coalition. The vector $\Upsilon(\boldsymbol{f})$ is said to be lexicographically greater than another vector $\Upsilon(\bar{\boldsymbol{f}})$ if there exists $h \leq 2^n-2$ such that $\Upsilon_i(\boldsymbol{f}) = \Upsilon_i(\bar{\boldsymbol{f}}), \forall 1 \leq i < h$ and $\Upsilon_h(\boldsymbol{f}) > \Upsilon_h(\bar{\boldsymbol{f}})$. We annotate $\Upsilon(\boldsymbol{f}) \succeq \Upsilon(\bar{\boldsymbol{f}})$. The nucleolus is defined as $\boldsymbol{f}$ that makes $\Upsilon(\boldsymbol{f}) \succeq \Upsilon(\bar{\boldsymbol{f}})$ for any $\bar{\boldsymbol{f}}$.

- **Tight Sets:** For the cost allocation $\boldsymbol{f}$, the following sets are defined: $\Psi_0(\boldsymbol{f}) = \{\{m\}, m = 1, ..., n : f_m = C(\{m\})\}$, $H_0(\boldsymbol{f}) = \{M\}$ and $H_k(\boldsymbol{f}) = H_{k-1}(\boldsymbol{f}) \cup \Psi_k(\boldsymbol{f})$. For $\forall k \geq 1$,

$$\varepsilon_k(\boldsymbol{f}) = \min_{S \notin H_{k-1}(\boldsymbol{f})} e(S, \boldsymbol{f}),$$

$$\Psi_k(\boldsymbol{f}) = \{S \notin H_{k-1}(\boldsymbol{f}) : e(S, \boldsymbol{f}) = \varepsilon_k(\boldsymbol{f})\}.$$

We regard $\Psi_k(\boldsymbol{f})$ as tight sets in the sense that all possible coalitions that can obtain the same excess $\varepsilon_k(\boldsymbol{f})$ are included. In particular, $\Psi_0(\boldsymbol{f})$ is the set of players that cannot gain cost savings from collaboration under the cost allocation $\boldsymbol{f}$; in other words, those players are on the boundary of violating their individual rationality.

- **Balancedness:** Given a set $K_0 \subseteq 2^M$, a set of coalitions $A \subseteq 2^M$ is called K_0-balanced if there exist vector $\tau \in \mathbb{R}_{\geq 0}^{|K_0|}$ and vector $\sigma \in \mathbb{R}_{>0}^{|A|}$ such that

$$\mathbf{u}(M) = \sum_{S \in K_0} \tau^\top \mathbf{u}(S) + \sum_{S \in A} \sigma^\top \mathbf{u}(S).$$

Here, $\boldsymbol{f}(S) = \sum_{m \in S} f_m = \boldsymbol{f}^\top \mathbf{u}(S), \forall S \subseteq M$. More specifically, if player m joins coalition S, its corresponding mth element in vector $\mathbf{u}(S)$ is 1, otherwise 0.

Example 5.1 *Given a 3-player game with costs* $C(\{1\}) = -1$, $C(\{2\}) = -2$, $C(\{3\}) = 5$, $C(\{1,2\}) = -6$, $C(\{1,3\}) = -7$, $C(\{2,3\} = -8$, *and* $C(\{1,2,3\}) = -12$. *If starting from imputation* $\boldsymbol{f}^0 = [-1, -4, -7]$, *then* $\varepsilon_1(\boldsymbol{f}^0) = -1$, $\Psi_0(\boldsymbol{f}^0) = \{\{1\}\}$, *and* $\Psi_1(\boldsymbol{f}^0) = \{\{1,2\}\}$. *Hence, the current tight set* $\Psi_1(\boldsymbol{f}^0)$ *is not* $\Psi_0(\boldsymbol{f}^0)$*-balanced. If we improve* $\boldsymbol{f}^1 = [-2.5, -4, -5.5]$*,then* $\varepsilon_1(\boldsymbol{f}^1) = 0.5$, $\Psi_0(\boldsymbol{f}^1) = \emptyset$, *and* $\Psi_1(\boldsymbol{f}^1) = \{\{1,2\}, \{3\}\}$. *After this step, we can see* $\Psi_1(\boldsymbol{f}^1)$ *is* $\Psi_0(\boldsymbol{f}^1)$*-balanced.* □

The proposed framework

We propose an efficient mechanism for computing the nucleolus, which addresses the challenge of calculating each possible coalitional cost for finding nucleolus when the cost is the output of a combinatorial optimization problem. The proposed framework of the mechanism is based on the Kohlberg criterion improved by [204] and [200]. However, their methods to calculate the nucleolus require that the cost of each possible coalition is known. This is quite challenging when each required cost is actually the output of a combinatorial optimization problem. To tackle this issue, in this work, we develop an efficient mechanism consisting of the verifying algorithm and the updating algorithm, which combines our HCBAP optimization model into the iterative search process of the nucleolus. This mechanism effectively avoids the complexity of calculating each possible coalitional cost but incorporates the characteristics of nucleolus to approach the nucleolus solution iteratively with the idea of gradient descent. As described in Algorithm 3, starting from a core solution obtained in Section 5.4.1, we verify if the current cost allocation is the nucleolus via the verifying algorithm. If the current cost allocation $\boldsymbol{f}$ passes the verifying algorithm, the nucleolus is found; otherwise, our updating algorithm determines which terminals' costs to increase or decrease and by how much, generating a new cost allocation vector that is then verified until the nucleolus is found.

Algorithm 3: The Framework for Calculating the Nucleolus

Input : grand coalition M, core solution $\boldsymbol{f}$
Output: The nucleolus solution $\boldsymbol{f}$

1 *Initialization:* $H_0 = \{M\}$ *and* $k = 1$, $\Psi_0 = \{\{m\} : f_m = C(\{m\}), m \in M\}$
2 Run verifying algorithm:
3 **while** $Rank(H_{k-1}) < n$ **do**
4   Calculate $\varepsilon_k = \min_{S \notin H_{k-1}} \{C(S) - \boldsymbol{f}(S)\}$;
5   Form $\Psi_k = \{S \notin H_{k-1} : e(S, \boldsymbol{f}) = \varepsilon_k\}$
6   **if** $\bigcup_{j=1}^{k} \Psi_j$ *is* Ψ_0*-balanced* **then**
7         $H_k = H_{k-1} \cup \Psi_k$, and $k = k+1$
8   **else**
9   Output the current largest Ψ_0-balanced set $U \subset \Psi_k$;
10         $\boldsymbol{f}$ is not the nucleolus, go to line 14
11 **if** $\boldsymbol{f}$ *is the nucleolus* **then**
12   stop
13 **else**
14   Run updating algorithm:
15   Generating direction $\boldsymbol{\lambda}$ and step size ρ;
16   Update $\boldsymbol{f} = \boldsymbol{f} + \rho\boldsymbol{\lambda}$;
17   Return to line 1

Verifying algorithm

The verifying algorithm is to verify if a cost allocation $\boldsymbol{f} = \{f_1, ...f_m\}$ is the nucleolus solution. As shown in Algorithm 3, the tight sets $\Psi_j (j = 1, 2, ...k)$ is formulated iteratively, observing $\varepsilon_1(\boldsymbol{f}) > \varepsilon_2(\boldsymbol{f}) > ... > \varepsilon_k(\boldsymbol{f})$. The algorithm stops either at line 10 of Algorithm 3, where the union of tight sets is found not Ψ_0-balanced, or at line 12 of Algorithm 3, where the rank of H_{k-1} reaches n. The output U_k is the union that satisfies Ψ_0-balancedness and contains the largest number of possible coalitions. $U = \Psi_k$ means the checkness is passed in this iteration k, while $U \subset \Psi_k$ means the Ψ_0-balancedness check fails. The cost allocation $\boldsymbol{f}$ that can pass the Ψ_0-balancedness check in each iteration $k < n$ is the nucleolus we are finding.

Updating algorithm

The adjustment is to keep the excess of coalitions that already pass the balancedness check but increase that of the most unsatisfied coalitions in the unbalanced set. The procedure to compute a direction vector $\boldsymbol{\lambda}$ and step size ρ is described in Algorithm 4, which is supported by Proposition 5.2 and Corollary 5.3.

Algorithm 4: Updating Algorithm for Generating $\boldsymbol{\lambda}$ and ρ

Input : Ψ_0, Ψ_k, U
Output: Direction vector $\boldsymbol{\lambda}$ and step size ρ
Initialization: $\Pi = \emptyset$
Obtain an adjusting direction $\boldsymbol{\lambda}$ via **UDP**
for $\forall S \in \mathcal{N}$ **do**
  if $1 - \boldsymbol{\lambda}(S) > 0$, *and* $1 - \boldsymbol{\lambda}(S) \notin \Pi$ **then**
    $\Pi = \Pi \cup \{1 - \boldsymbol{\lambda}(S)\}$
$\rho = -\infty$
for $\forall \chi \in \Pi$ **do**
  $obj = \max\big(\varepsilon_k(\boldsymbol{f}) - e(S, \boldsymbol{f})\big)$
  s.t. $1 - \boldsymbol{\lambda}(S) = \chi$
  if $\frac{obj}{\chi} > \rho$ **then**
    $\rho = \frac{obj}{\chi}$
$\rho = \max \Big(\{\frac{C(\{j\}) - f_j}{\lambda_j} : \lambda_j < 0\} \cup \rho\Big)$

Remark 5.2 If there exists a coalition $\bar{S}$ (possibly more than one) such that $\varepsilon_k(\boldsymbol{f} + \rho\boldsymbol{\lambda}) = e(\bar{S}, \boldsymbol{f} + \rho\boldsymbol{\lambda})$ at iteration k, then when $\boldsymbol{\lambda}(S) < 1$, $\boldsymbol{\lambda}(\bar{S}) \geq 1$ and $\rho < 0$, the distance between the excess of each coalition and the current minimal satisfaction decreases after adjustment. □

Proof: $\forall S \in M$, at iteration k, the change of excess after adjustment is $e(S, \boldsymbol{f} + \rho\lambda) - e(S, \boldsymbol{f}) = C(S) - \big(\boldsymbol{f}(S) + \rho\boldsymbol{\lambda}(S)\big) - \big(C(S) - \boldsymbol{f}(S)\big) = -\rho\boldsymbol{\lambda}(S)$. The distance between the excess of each coalition and the current minimal satisfaction for $\boldsymbol{f}$ is $\ell(\boldsymbol{f}) = e(S, \boldsymbol{f}) - \varepsilon_k(\boldsymbol{f})$, and for $\boldsymbol{f} + \rho\boldsymbol{\lambda}$, it is $\ell(\boldsymbol{f} + \rho\lambda) = e(S, \boldsymbol{f} + \rho\lambda) - \varepsilon_k(\bar{S}, \boldsymbol{f} + \rho\lambda)$. The gap in the distance after adjustment is $\Delta = \ell(\boldsymbol{f} + \rho\boldsymbol{\lambda}) - \ell(\boldsymbol{f}) = \rho\big(\boldsymbol{\lambda}(\bar{S}) - \boldsymbol{\lambda}(S)\big) \leq \rho\big(1 - \boldsymbol{\lambda}(S)\big) < 0$. □

Based on Remark 5.2, we formulate the following model, denoted as **UDP**, to find an adjusting direction $\boldsymbol{\lambda}$.

$$\min \sum_{\Omega \in \Psi_k \setminus U} \sum_{j \in \Omega} \lambda_j \tag{5.37}$$

Subject to:

$$\sum_{j \in \Omega} \lambda_j \geq 1 \quad \forall \Omega \in \Psi_k \setminus U \tag{5.38}$$

$$\sum_{j \in \Omega} \lambda_j \geq 0 \quad \forall \Omega \in \Psi_0 \tag{5.39}$$

$$\sum_{j \in \Omega} \lambda_j = 0 \quad \forall \Omega \in U \setminus \Psi_k \tag{5.40}$$

Recall that three sets are formed when we check the Ψ_0-balancedness: Ψ_0, Ψ_k, and U. Ψ_0 contains all players whose distributed costs cannot be increased, that is, they are on the boundary of violating individual rationality. Ψ_k is the tight set, and U is the largest Ψ_0-balanced set. We aim to find one coalition $\bar{S}$ satisfying Remark 5.2 restricted in set $\Psi_k \setminus U$, which can guarantee the balanced set unchanged. The optimal solution is to find a direction vector satisfying $\boldsymbol{\lambda}(\bar{S}) = 1$, $\boldsymbol{\lambda}(S) < 1$, and $\Delta < 0$.

Remark 5.3 At iteration k, for $\forall \boldsymbol{\lambda}(S) < 1$ and $\rho < 0$,

$$\rho \geq \frac{\varepsilon_k(\boldsymbol{f}) - e(S, \boldsymbol{f})}{1 - \boldsymbol{\lambda}(\boldsymbol{S})}.$$

□

Example 5.4 *For any S at iteration k, $e(S,\boldsymbol{f}) \geq \varepsilon_k(\boldsymbol{f})$. Thus, $e(S,\boldsymbol{f}+\rho\boldsymbol{\lambda}) = e(S,\boldsymbol{f}) - \rho\boldsymbol{\lambda}(S) \geq \varepsilon_k(\boldsymbol{f}+\rho\boldsymbol{\lambda}) = \varepsilon_k(\boldsymbol{f}) - \rho\boldsymbol{\lambda}(\bar{S})$. After rearranging, we get $e(S,\boldsymbol{f}) + \rho\big(\boldsymbol{\lambda}(\bar{S}) - \boldsymbol{\lambda}(S)\big) \geq \varepsilon_k(\boldsymbol{f})$. Given $\boldsymbol{\lambda}(\bar{S}) = 1$ and $\boldsymbol{\lambda}(S) < 1$, $\rho \geq \frac{\varepsilon_k(\boldsymbol{f}) - e(S,\boldsymbol{f})}{1-\boldsymbol{\lambda}(S)}$.* □

As we decrease ρ from 0, the smallest moving step should be the largest ρ. Therefore, for cost allocation $\boldsymbol{f}$ at iteration k, the following model is proposed to calculate the adjusting step size ρ.

$$\max \quad \frac{\varepsilon_k(\boldsymbol{f}) - e(S, \boldsymbol{f})}{1 - \boldsymbol{\lambda}(S)} \tag{5.41}$$

Subject to:

$$\boldsymbol{\lambda}(S) < 1 \tag{5.42}$$

Specifically, the objective function (5.41) is non-linear. Thus, we decompose the problem into several subproblems. The general procedure is to group S with the same value of $1 - \boldsymbol{\lambda}(S)$, and then find the maximum value of $\varepsilon_k(\boldsymbol{f}) - e(S, \boldsymbol{f})$ within each group. Finally, we choose the maximum one among all groups. The details are described from line 3 to line 11 in Algorithm 4. Besides, individual rationality should also be considered. Therefore, at iteration k, the step size is:

$$\rho = \max\left(\left\{\frac{\varepsilon_k(\boldsymbol{f}) - e(S,\boldsymbol{f})}{1 - \boldsymbol{\lambda}(S)} : \boldsymbol{\lambda}(S) < 1\right\} \cup \left\{\frac{C(\{j\}) - f_j}{\lambda_j} : \lambda_j < 0\right\}\right).$$

5.4.3 Illustrative example for comparing the core and the nucleolus

We have shown the overall cost savings for all terminals participating in the collaboration. In this section, we focus on the cost allocated to the individual terminal so that they will stay in the coalition, in other words, maintaining collaboration stability. First, we illustrate a small instance's core and nucleolus relationship with $|N| = 10$, $|M| = 3$, and $|B_m| = 3$. The results are shown in Table 5.3. In this case, the cost of grand coalition is $C(\{1,2,3\}) = 3243$, and the stand-alone cost of each terminal is $C(\{1\}) = 939$, $C(\{2\})$, and $C(\{3\}) = 1693$.

Table 5.3: Results of an illustrative example.

Terminal	Stand-alone	RG-based Core		The Nucleolus	
		Cost	Improvement	Cost	Improvement
1	939.00	939.00	0.00%	939.00	0.00%
2	1482.00	1086.7	26.67%	1038.60	29.91%
3	1693.00	1217.3	28.09%	1265.40	25.26%
Total	4114.00	3243.00	21.17%	3243.00	21.17%

Figure 5.4 presents the individual cost of each terminal by two different cost allocation methods. Compared with the stand-alone method, individual costs of two terminals are reduced by joining the collaboration, and one remains the same.

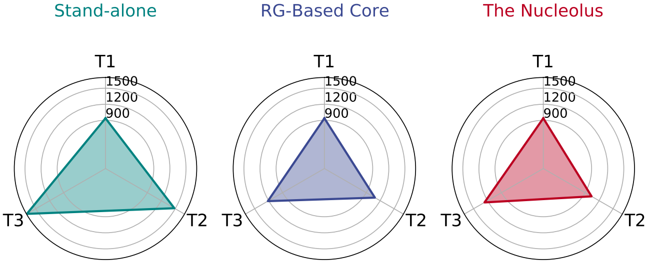


Figure 5.4: Different individual costs of an illustrative example with three Terminals.

We use Barycentric coordinates to illustrate the cost allocation in Figure 5.5, where the vertex is defined as the maximum cost (stand-alone cost) each terminal can accept, and each point inside the triangle represents a cost allocation. The definition of the core maps a stable area in which there is no incentive for terminals to leave the grand coalition. As can be seen, the RG-based core falls into the stable zone, and the nucleolus is also in the core.

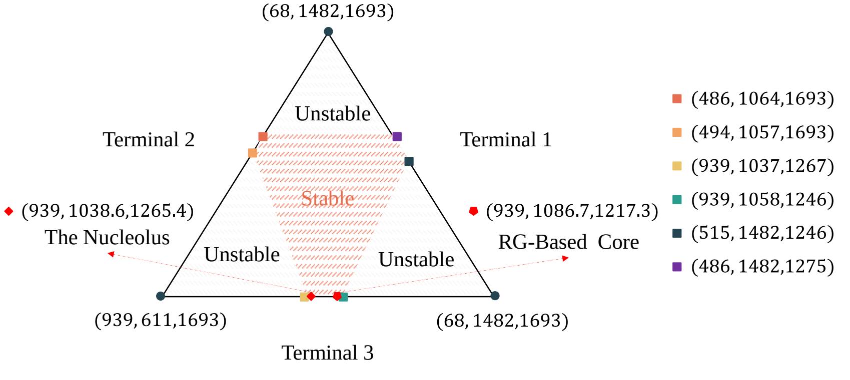


Figure 5.5: Illustration of the relationship between RG-based core and the nucleolus.

5.5 Computational experiments

This section conducts numerical experiments to evaluate the performance of the proposed HCBAP model and the developed cost allocation algorithms for the stability of collaboration. The MILP model is solved using CPLEX 12.7 with a time limit of 7200 seconds. We code the presented algorithms in C++, and the experiments are conducted on the computer using one node with 12 cores, 2x Intel XEON E5-6248R 24C 3.0GHz, and 192GB of RAM.

5.5.1 Instances

We created instances containing three vessel classes with the corresponding cost rates [142] and loaded or discharged container quantity [136], shown in Table 5.4. The notation U represents a uniform distribution of the given range. The vessel set of each instance consists of 60% Feeder, 30% Medium, and 10% Jumbo. The expected arrival time is randomly generated within the planning horizon (T = 168h), and the expected departure time is also obtained successively. The number of QCs equipped at each terminal is set between 2 to 10. Besides, each terminal's cost rate of QC service is set as $c^{\kappa} = 10$ [142]. We pre-set the terminal where each vessel is contracted to visit, and the distance between terminals is generated randomly.

Table 5.4: Vessel-related parameters setting (unit is given in 10 dollars).

Class	Unit Cost of Vessel $i \in V$			Container Quantity(g_i)
	QC-hour demand (w_i)	Waiting (c_i^{ω})	Tardness (c_i^{δ})	
Feeder	U[5,15]	U[100,199]	U[100,199]	U[500,3500]
Medium	U[15,50]	U[200,299]	U[200,299]	U[3500,5000]
Jumbo	U[50,65]	300	300	U[5000,7500]

5.5.2 Improvement with the HCBAP model

To evaluate the effectiveness of the proposed collaborative strategy for berth allocation, we compare the results of our HCBAP model with the stand-alone planning method. The stand-alone method reflects an independent decision-making process without collaboration among terminals: the vessel can only wait at the contracted terminal until there are available berths and QCs. To compare the HCBAP model's performance in dealing with disruption caused by vessel delay, we define total berthing costs indicated by the objective function as recovery costs when testing the model in cases of disruptions.

In Table 5.5, the first column states the instance properties, including the number of vessels $|V|$, the number of terminals $|M|$, and the number of berths at each terminal $|B_m|$. The columns denoted by "Z" show the total cost defined by function (5.1). Besides, "C_{delay}" reports the cost of tardiness caused by vessel delay, and "C_{trans}" displays the container transshipment cost because of vessel transfer between terminals. The column "T_{opt}" is the time for solving the HCBAP model. The increase in transshipment cost, the decrease in tardiness cost, and the total cost savings by the HCBAP model are indicated in column"IC_{trans}", "DC_{delay}", and "Z_{save}" respectively.

Table 5.5: Comparison between HCBAP model and stand-alone method.

Instance	Stand-alone Method			HCBAP Model				Improvement		
$\lvert V\rvert-\lvert M\rvert-\lvert B_m\rvert$ (1)	Z (2)	C_{trans} (3)	C_{delay} (4)	Z (5)	T_{opt} (6)	C_{trans} (7)	C_{delay} (8)	IC_{trans} (9)	DC_{delay} (10)	Z_{save} (11)
10-3-3	4010.00	0.00	2306.67	2419.80	16.85	156.46	560.00	3.90%	43.56%	39.66%
10-5-3	3592.67	0.00	1619.33	2826.68	4.04	130.34	723.00	3.63%	24.95%	21.32%
12-3-4	3989.33	0.00	1872.67	3318.33	9.13	150.33	1051.33	3.77%	20.59%	16.82%
12-5-4	5942.33	0.00	2599.00	4670.84	44.06	213.51	1114.00	3.59%	24.99%	21.40%
18-3-4	6905.67	0.00	3715.67	4586.02	14.03	161.68	1234.33	2.34%	35.93%	33.59%
18-4-5	5699.67	0.00	2749.67	4567.96	36.86	234.96	1416.33	4.12%	23.39%	19.86%
20-4-5	7647.33	0.00	4094.00	5164.93	89.04	362.93	1248.67	4.75%	37.21%	32.46%
20-5-5	5952.33	0.00	2682.33	4636.83	67.97	247.14	1119.67	4.15%	26.25%	22.10%
25-5-5	8314.00	0.00	4150.67	6496.58	428.29	355.91	1977.33	4.28%	26.14%	21.86%
28-5-6	13015.00	0.00	6838.33	8728.07	216.58	526.73	2024.67	4.05%	36.99%	32.94%
30-6-6	9147.00	0.00	4677.00	7052.57	132.57	419.24	1833.33	4.58%	31.09%	22.90%
35-6-7	15835.00	0.00	7491.67	11085.76	453.51	738.09	2004.33	4.66%	34.65%	29.99%
40-6-8	21452.80	0.00	7405.00	12678.57	2479.23	902	3027.00	4.20%	59.12%	40.90%
45-7-8	22079.00	0.00	12159.00	12735.38	5507.40	945.38	1870.00	4.28%	46.60%	42.32%
Average	-	-	-	-	-	-	-	4.02%	33.68%	28.44%
10-3-3-dr	5262.67	0.00	3559.33	3304.77	25.23	165.77	1065.67	3.15%	70.06%	37.20%
10-5-3-dr	4876.67	0.00	2903.33	3605.09	1.58	132.75	1499.00	2.72%	48.37%	26.07%
12-3-4-dr	5417.33	0.00	3300.67	4099.99	1.13	186.66	1796.67	3.45%	45.57%	24.32%
12-5-4-dr	7841.33	0.00	4498.00	5946.87	24.47	237.54	2366.00	3.03%	47.40%	24.16%
18-3-4-dr	10065.67	0.00	6849.00	6288.21	7.92	205.21	2893.00	2.04%	57.76%	37.53%
18-4-5-dr	7518.33	0.00	4601.67	5877.75	22.45	247.42	2713.67	3.29%	41.03%	21.82%
20-4-5-dr	8867.67	0.00	5281.00	5862.39	118.76	409.73	1899.33	4.62%	64.03%	33.89%
20-5-5-dr	9112.67	0.00	5842.67	6198.61	50.01	337.28	2591.33	3.70%	55.65%	31.98%
25-5-5-dr	13959.00	0.00	7563.67	8251.23	53.81	406.90	3681.00	2.91%	51.33%	40.89%
28-5-6-dr	17516.13	0.00	10894.67	11701.61	224.35	582.61	4942.33	3.33%	54.64%	33.20%
30-6-6-dr	15089.67	0.00	10286.33	8591.81	408.07	442.81	3349.00	2.93%	67.44%	43.06%
35-6-7-dr	23001.33	0.00	11749.00	14146.30	563.46	827.63	4975.33	3.60%	57.65%	38.50%
40-6-8-dr	22898.80	0.00	8798.00	13758.43	473.03	761.43	4247.00	3.33%	51.73%	39.92%
45-7-8-dr	37576.60	0.00	14937.00	17315.72	1453.04	976.72	6419.00	2.60%	57.03%	53.92%
Average	-	-	-	-	-	-	-	3.19%	54.98%	34.75%

We test 28 instance scales with up to 45 vessels and seven terminals. Instances with "−dr" represent the disruption caused by arrival delays of calling vessels in this paper. The average results of three different instances for each scale are displayed in Table 5.5. As seen in the table, while the collaborative strategy can incur extra container movements between terminals (denoted by the parameter c^1_{im}), the HCBAP model exhibits significant potential in alleviating the overall costs incurred by all terminals through the reduction of time inefficiencies resulting from vessels awaiting service at their designated terminal. Regarding the instances without disruption, although collaborative berth planning incurs extra transshipment costs $\mathrm{C}_{\mathrm{trans}}$, it dramatically reduces the tardiness cost $\mathrm{C}_{\mathrm{delay}}$. On average, with a 4.02% increase in transshipment cost, the tardiness cost can be decreased by around 33.68%; consequently, our model can result in around 28.44% savings for the total cost. Our HCBAP model also performs well when dealing with disruption, with around 34.75% savings compared with the stand-alone method. Furthermore, the reduction of vessel tardiness also shows excellent potential for releasing port congestion. Thus, the HCBAP model proposed in this paper significantly improved over the stand-alone method without collaboration.

To show the effectiveness of the proposed HCBAP model in dealing with disruptions, we compare extra costs after disruptions, with and without collaboration in Figure 5.6. As we can see from the figure, our HCBAP model significantly decreases the recovery costs. In other words, our HCBAP model can significantly lower the recovery costs in disruptive scenarios caused by arrival delays of calling vessels. In this regard, it contributes to the enhancement of resilience.

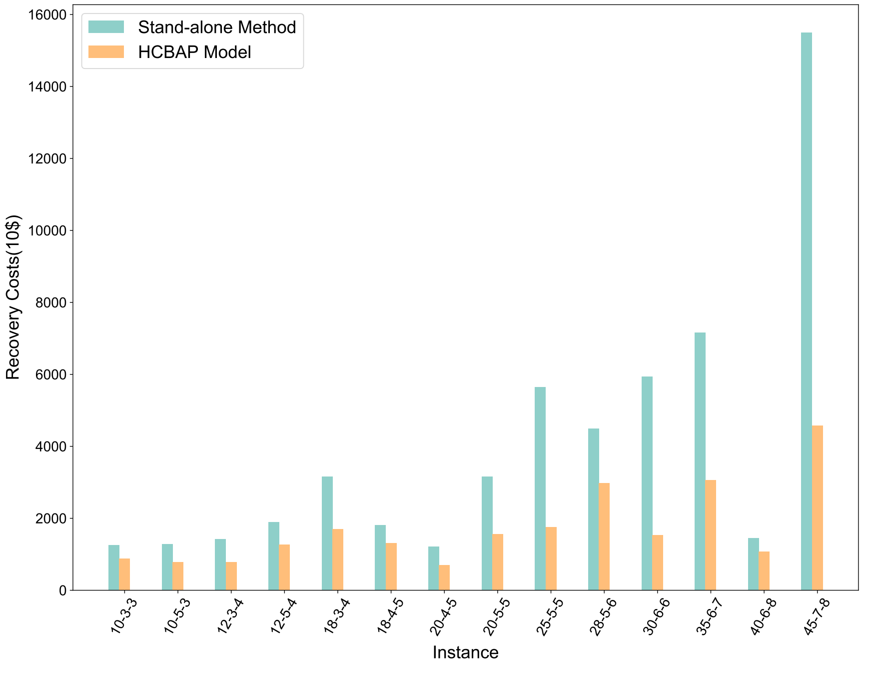


Figure 5.6: Comparison of recovery costs between stand-alone method and our HCBAP model.

5.5.3 Results of cost allocations by RG-based core and the nucleolus

In this section, we have calculated the core and the nucleolus based on cooperative game theory to allocate the coalitional costs among collaborative terminals. As described in Section 5.4, the calculation of the core and the nucleolus requires multiple iterations of the MILP model, and thus it is computationally quite challenging even with a limited number of participants. For example, the instance of 10-3-3-I1, takes 2227.34 seconds to solve the BAP in a one-player setting, if we want to obtain the core and the nucleolus solutions, we need to solve this BAP for every subset of players. This leads to a computational time of $2227.34 \times 7 = 15591.38 \simeq 4.33h$, for the smallest considered instance 10-3-3 in Table 5.6. For the largest instance 30-6-6-I2, it takes 7208.84 seconds in the one-player setting, and the expected time to obtain core and nucleolus solutions can come to $7208.84 \times (26-1) \simeq 126h$, that is, more than 5 days. The accepted computational time for operational BAP is within the maximum 3 hours [38]. Thus, enumeration is impossible while our proposed algorithms can find the results within 7200s.

For evaluating the performance of the proposed algorithms for calculating the core and the nucleolus, in this section, we compare the cost allocation results for individuals obtained by our algorithms with those obtained by the Proportional to Stand-alone Costs (PSC) method [124]. The PSC method distributes costs among all players according to their stand-alone costs, and the formulation of PSC is as follows:

$$f_i = \frac{C(\{i\})}{\sum_{j \in M} C(\{j\})} C(M),$$

where f_i is the cost allocated to player i, $C(\{j\})$ is the stand-alone cost of player j, and $C(M)$ is the coalitional cost of the grand coalition M.

There are two main allocation concepts in cooperative that grant stability in cooperative game theory: the core and the nucleolus. We provide exact solutions for both methods. That is, we can claim with certainty that the provided allocations are stable in terms the relevant theoretical foundations. We present the numerical results of our RG-based Core and the nucleolus in Table 5.6, comparing them with the PSC method. In addition to the same notations as Table 5.5, for each cost allocation method, we report the total cost of grand coalition "Z_{HCBAP}", the running time in seconds "Time", the number of terminals that can obtain cost savings "NO_{m}", and the minimum percentage of individual cost savings "Min", the maximum value"Max" as well as the average value "Ave". Individual rationality has been considered a necessary condition in the core and the nucleolus; thus, we only check that for the PSC method, represented by " IR".

As we can see from column (3) in Table 5.6, using the PSC cost allocation method, only 16 of 33 instances can satisfy the requirement of individual rationality, which means the individual terminal will cost more within collaboration than without in most cases. Compared with PSC, the definition of our RG-based core and the nucleolus have considered individual rationality as strict constraints, guaranteeing no terminals perform worse than working alone. Notably, in columns (10) and (15), 0.00% cost savings means there are some terminals whose costs in the collaboration are the same as working alone. As long as the costs are not increased, for those terminals, there are many other benefits to form the coalition. For example, by joining the coalition, they can improve their service level by providing more candidate space for their customers. It may not bring extra profits in some instances, but it may save a lot in other cases. No matter in which cases, they will not perform worse than working alone. Therefore, we can say the coalition is stable as long as there is no worse performance in profits in the coalition than working alone. However, by the PSC cost allocation method, many negative figures are shown in columns (5), implying that some players whose costs have even increased after joining the collaboration; for those players, they may choose to leave the coalition, and thus, the collaboration is unstable. Comparing the last row of columns (5), (10), and (15), the average of the minimum cost savings for all 33 instances is -15.76% by the PSC method, while it is 0.00% by our RG-based Core and 4.48% by the nucleolus, showing a considerable improvement on collaboration stability by the proposed RG-based Core and the nucleolus than the PSC method.

In Figure 5.7, we illustrate the great deviation of the cost allocation obtained by the PSC compared with the proposed RG-based core and the nucleolus for individual terminals in the coalition. It further highlights the necessity of applying the proposed cost allocation methods rather than the naive PSC method.

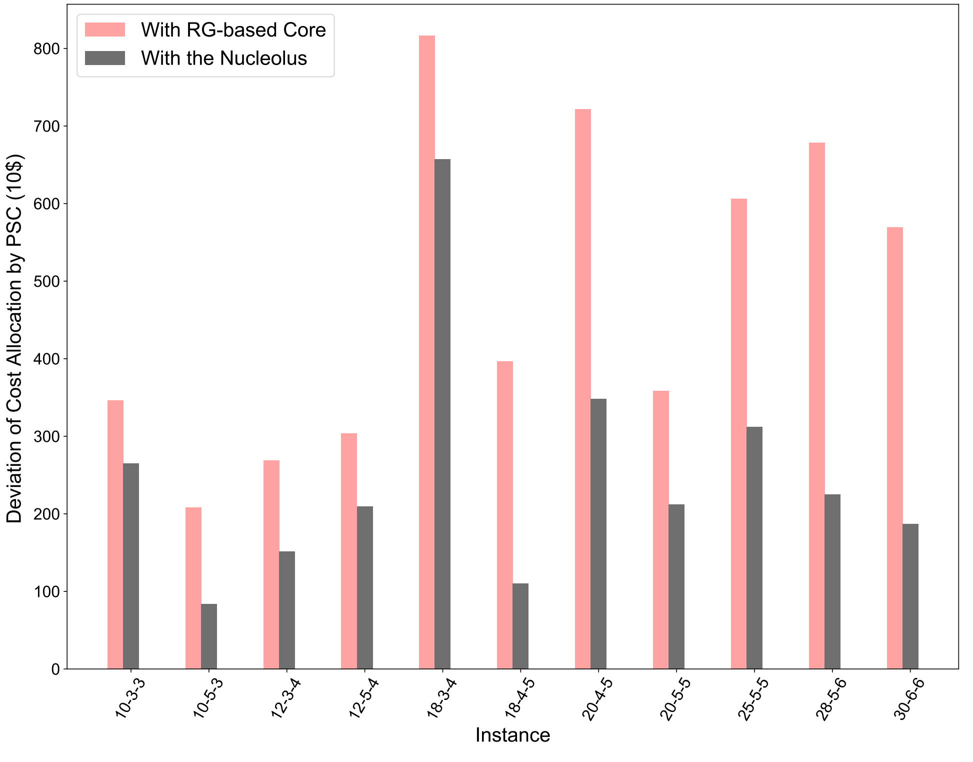


Figure 5.7: Deviation of PSC compared with RG-based core and the nucleolus.

Table 5.6: Numerical results of RG-based core and the nucleolus.

Instance		PSC Method [124]					RG-based Core					The Nucleolus				
$\lvert V\rvert-\lvert M\rvert-\lvert B_m\rvert-ID$	Z_{HCBAP}	IR	No_m	Min	Max	Ave	Time	No_m	Min	Max	Ave	Time	No_m	Min	Max	Ave
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
10-3-3-I1	2340.00	✓	3	51.05%	89.31%	65.87%	112	2	0.00%	100.00%	54.07%	782	2	0.00%	74.90%	38.94%
10-3-3-I2	2700.90	✓	3	21.03%	41.27%	34.11%	94	1	0.00%	57.25%	19.08%	201	2	0.00%	29.93%	19.28%
10-3-3-I3	2218.19	-	2	-2.90%	31.43%	19.27%	43	1	0.00%	77.21%	25.74%	56	2	0.00%	54.71%	31.82%
10-5-3-I1	2655.48	-	4	-88.20%	37.40%	7.39%	170	2	0.00%	100.00%	26.08%	8128	5	4.35%	38.34%	25.74%
10-5-3-I2	2689.29	✓	5	19.84%	61.93%	47.42%	67	1	0.00%	80.50%	16.10%	1712	4	0.00%	37.02%	19.48%
10-5-3-I3	2501.59	-	3	-87.37%	24.10%	-9.43%	310	2	0.00%	100.00%	31.81%	2318	4	0.00%	45.21%	23.56%
12-3-4-I1	3046.88	✓	3	15.60%	53.42%	36.67%	63	1	0.00%	36.52%	12.17%	24	2	0.00%	23.45%	13.82%
12-3-4-I2	3152.78	-	1	-25.77%	22.40%	-4.08%	28	1	0.00%	73.23%	24.41%	76	2	0.00%	41.69%	26.28%
12-3-4-I3	3755.33	✓	3	12.57%	62.19%	31.47%	73	1	0.00%	23.91%	7.97%	119	2	0.00%	27.38%	12.80%
12-5-4-I1	3592.20	✓	5	6.57%	68.75%	34.30%	47	1	0.00%	24.01%	4.80%	263	2	0.00%	11.25%	4.16%
12-5-4-I2	4054.55	✓	5	11.34%	83.09%	44.34%	195	3	0.00%	100.00%	42.07%	1118	3	0.00%	100.00%	27.26%
12-5-4-I3	4808.75	✓	5	16.46%	58.93%	34.76%	25	1	0.00%	54.96%	10.99%	3721	3	0.00%	48.48%	18.01%
18-3-4-I1	4752.79	-	2	-99.82%	12.15%	-40.28%	30	1	0.00%	38.66%	12.89%	119	2	0.00%	27.90%	14.68%
18-3-4-I2	4604.88	✓	3	20.80%	60.30%	40.45%	47	1	0.00%	87.19%	29.06%	522	2	0.00%	70.97%	34.44%
18-3-4-I3	4400.38	-	1	-12.46%	42.09%	7.90%	49	2	0.00%	100.00%	54.12%	506	2	0.00%	85.51%	54.57%
18-4-5-I1	4575.86	-	3	-3.49%	49.50%	21.95%	58	1	0.00%	52.58%	13.14%	6808	4	7.86%	28.86%	21.12%
18-4-5-I2	4004.69	✓	4	22.85%	52.35%	41.91%	241	1	0.00%	91.18%	22.80%	3627	3	0.00%	34.30%	21.21%
18-4-5-I3	4122.58	-	3	-56.83%	34.27%	1.41%	43	1	0.00%	67.34%	16.83%	3374	4	13.51%	32.80%	24.45%
20-4-5-I1	5032.56	-	3	-19.80%	39.56%	17.59%	59	1	0.00%	69.70%	17.42%	5510	4	11.38%	33.56%	19.38%
20-4-5-I2	4744.90	✓	4	36.50%	81.20%	59.43%	92	1	0.00%	81.89%	20.47%	4718	3	0.00%	62.18%	26.12%
20-4-5-I3	5717.34	✓	4	37.97%	71.69%	53.23%	79	2	0.00%	100.00%	42.25%	9867	4	7.14%	66.12%	31.48%
20-5-5-I1	5032.56	✓	5	8.68%	38.29%	24.07%	63	2	0.00%	100.00%	24.14%	9215	5	10.52%	38.08%	25.98%
20-5-5-I2	5717.34	-	4	-10.33%	29.37%	14.13%	66	2	0.00%	100.00%	21.29%	4636	5	12.75%	38.14%	24.89%
20-5-5-I3	6427.92	-	1	-92.77%	6.05%	-41.13%	195	2	0.00%	100.00%	20.79%	11147	5	1.12%	32.90%	21.24%
25-5-5-I1	4914.55	-	3	-64.10%	36.63%	2.93%	83	2	0.00%	100.00%	24.92%	7784	5	17.09%	35.44%	25.88%
25-5-5-I2	4637.01	✓	5	27.80%	41.69%	35.13%	629	2	0.00%	100.00%	20.68%	23006	5	3.72%	42.61%	21.87%
25-5-5-I3	4718.05	✓	5	8.84%	40.44%	24.46%	67	1	0.00%	54.27%	10.85%	1746	2	0.00%	36.64%	10.56%
28-5-6-I1	8242.96	-	3	-22.75%	41.38%	5.80%	181	1	0.00%	63.45%	12.87%	54632	5	5.53%	35.72%	22.49%
28-5-6-I2	6958.65	-	4	-0.03%	40.71%	22.92%	238	2	0.00%	100.00%	24.05%	38183	5	24.73%	40.07%	29.66%
28-5-6-I3	8433.45	-	1	-178.15%	23.44%	-79.64%	101	2	0.00%	100.00%	20.48%	48793	5	6.76%	37.09%	20.58%
30-6-6-I1	7282.64	-	5	-12.82%	31.73%	14.09%	151	2	0.00%	100.00%	25.83%	43352	4	0.00%	48.70%	27.73%
30-6-6-I2	6796.29	✓	6	14.03%	54.12%	29.33%	174	2	0.00%	100.00%	17.01%	34083	6	7.67%	29.43%	19.97%
30-6-6-I3	7078.78	-	4	-74.37%	37.08%	1.79%	355	2	0.00%	100.00%	30.95%	86400	6	13.87%	40.82%	29.94%
Average				-15.76%	45.40%	18.17%			**0.00%**	**79.81%**	**22.97%**			**4.48%**	**43.34%**	**23.92%**

By analyzing the number of terminals that obtain individual cost savings shown in columns (9) and (14) of Table 5.6, we observe that the nucleolus solution can always make more terminals gain benefits than the RG-based core solution. This effect is gradually remarkable in larger instances with more vessels and terminals. That means more individual terminals can be firmly convinced not to leave the coalition; thus, collaboration stability is improved. The minimum and maximum cost savings among terminals further confirm our observation. As seen from Figure 5.8, the statistical analysis reveals that the nucleolus method can produce superior individual cost savings compared to the RG-based core. The average minimum cost savings of the nucleolus solution is 4.48%, larger than 0.00% of the RG-based core solution, emphasizing the critical role of the nucleolus in strengthening collaboration stability. In contrast, the average maximum savings is 79.81% in the core, while it turns smaller to 43.34% in the nucleolus solution. Consequently, compared to the RG-based Core, the nucleolus significantly decreases the variance of individual cost savings by 49.67% (on average of all considered instances), indicating that more terminals gain from the cost savings generated by collaboration, and consistently establishing stronger collaboration incentives for terminals.

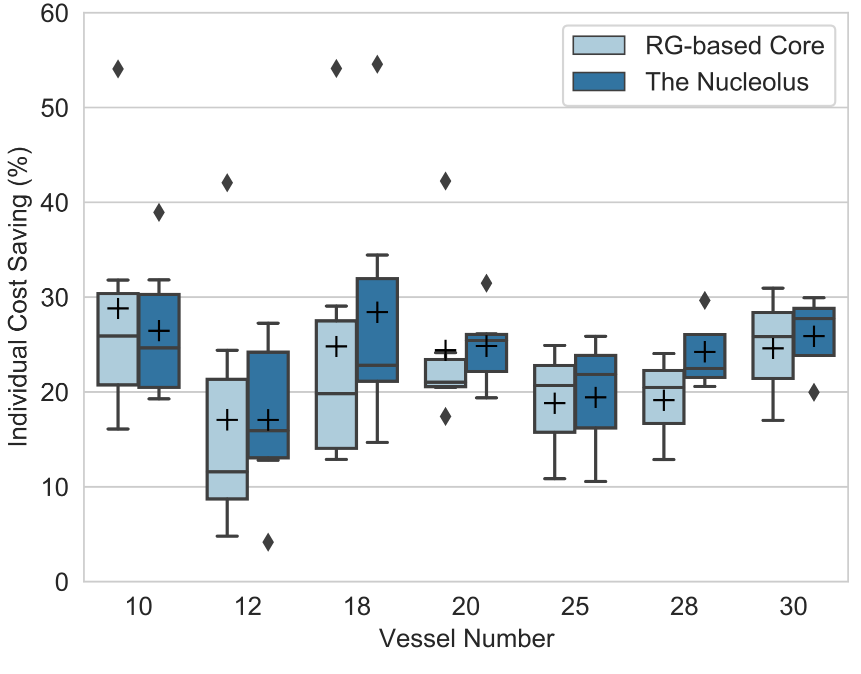


Figure 5.8: Analysis of individual cost savings for instances with different vessel size.

As shown in Figure 5.9, the difference between Min and Max of the RG-based core is considerably larger than that of the nucleolus. In other words, the nucleolus solution allocates the total cost savings brought by collaboration more "evenly" to each terminal. Thus, more terminals benefit from collaboration so that they have a clear incentive to collaborate, and thereby, the stability is further enhanced.

From the computational time shown in Table 5.6, we can also see that finding a core

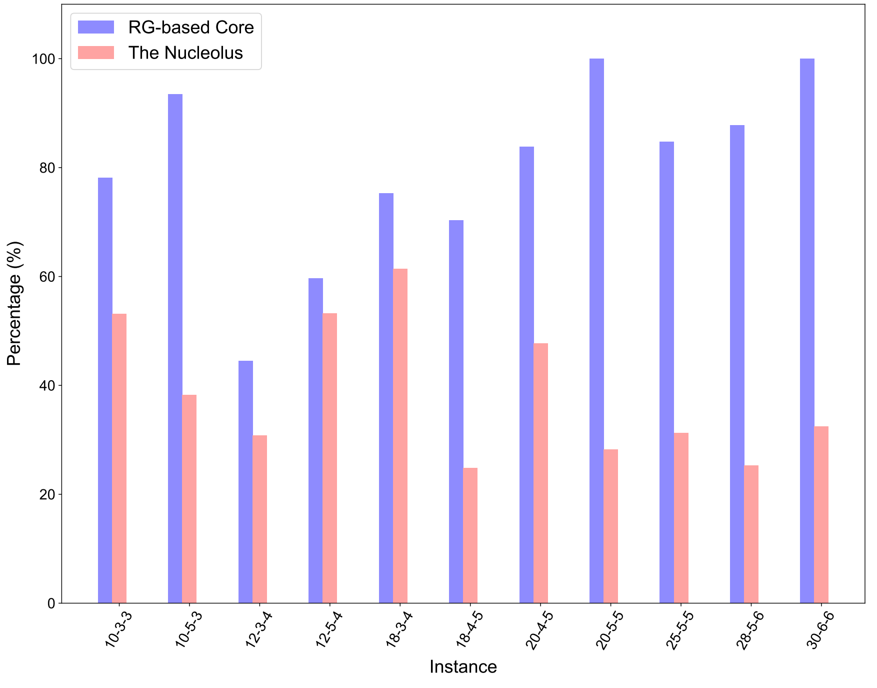


Figure 5.9: Difference between Max and Min of RG-based core and the nucleolus.

solution is much faster than finding a nucleolus solution. Thus, the decision-makers can choose the cost allocation strategy according to practical situations. When the core solution is not satisfying enough to convince individual terminals, the nucleolus solution becomes more significant even though its calculation is time-consuming.

5.6 Discussion and key insights

The following discussion presents key findings from our study on horizontal collaborative berth planning. While the collaborative strategy can incur extra container movements between terminals, the proposed berth allocation based on inter-terminal collaboration exhibits significant potential in alleviating the overall costs by reducing time inefficiencies resulting from vessels awaiting service at their designated terminal. These findings highlight the potential of collaboration in cost savings and facilitate its practical implementation. The following are the main findings:

(1) *The proposed collaborative berth allocation approach demonstrates a significant cost reduction potential for terminal operators, in both conventional and disruptive scenarios:* Our experimental results showcase significant (28.44%) savings in overall costs in conventional scenarios. Specifically, despite a 4.02% increase in transhipment costs, the tardiness cost decreased by around 33.68%. In disruptive scenarios, the total cost savings reach 34.75% with a notable reduction of 54.98% in tardiness

costs, indicating the positive impact of terminal collaboration on alleviating port congestion after disruptions.

(2) *Collaboration among terminals is an effective means to reduce recovery costs after disruptions:* In managing disruptions, terminal operators have to face additional costs associated with berthing plan adjustment, referred to as recovery costs. However, our results indicate that collaboration among terminals provides an economically viable opportunity for vessels to transfer to another terminal for earlier service. On average, the proposed collaborative berth allocation approach has been shown to reduce recovery costs by 54%, with a range of 30% to 70%, thus significantly enhancing the resilience of terminal operations.

(3) *Stable and attractive collaboration incentives (with the core and nucleolus) can be achieved at a moderate cost:* Terminal operators may decline to join a coalition if they do not see clear benefits by comparing their individual costs/gains in a collaborative setting vs. a non-cooperative setting (also referred to as a stand-alone setting). The results of our numerical experiments calculating the core and the nucleolus ensure that the cost allocated to individual terminals does not exceed their stand-alone costs, on average, achieving savings of 22.97% and 23.92% for individual costs, respectively, thereby maintaining stable collaboration incentives. That is, ensuring stable and attractive collaboration incentives (based on the core and nucleolus) results in average savings that are only about 5 percentage points lower than the hypothetical collaboration optimum (28.44%).

(4) *Simple allocation methods bear the risk of unstable collaboration incentives:* Applying the PSC cost allocation method [124], which distributes costs based on standalone costs, the experimental results reveal an undesirable trend. In over half of the instances (17 out of 33) examined, individual costs for terminal operators remained increasing despite a decrease in overall costs. The PSC cost allocations have largely deviated from our RG-based core and the nucleolus solution, where the maximum deviation of individual costs with RG-based core and the nucleolus can occupy 36.27% and 35.26% of the total costs, respectively. These findings highlight the inherent instability of collaboration among terminal operators when cost allocations provided by the core and nucleolus are not adequately considered.

(5) *The nucleolus increases the number of terminals benefiting from collaboration for all instances:* In our experimental instances, the nucleolus solution outperforms the RG-based core in all instances examined regarding the number of terminals achieving cost reductions. That is, the nucleolus allocations yield more terminals with actual improvements, while the core solutions have more terminals that do not improve (i.e., remain with the standalone costs) by collaboration. Moreover, compared to the RG-based core solution, the nucleolus significantly decreases the variance of individual cost savings in a coalition by 49.67% (on average over all considered instances), indicating that more terminals gain from the cost savings generated by collaboration. Thus, the nucleolus solutions consistently establish stronger collaboration incentives for terminals.

5.7 Conclusions

Collaboration has become vitally important as a strategy in the maritime sector to respond to disruptions in global supply chain networks, for instance, imposed by the COVID-19 pandemic or the Red Sea crisis. The container crisis further highlighted that container terminals have a crucial role as scarce resources in these global networks. As a result, new alliances and digital platforms are introduced in an attempt to facilitate collaborative planning of maritime transport operations. Related research, nevertheless, often either entirely disregards the collaboration incentives of the involved parties or assumes unrealistically small problem sizes, which significantly limits the application potential for real-world problems. Consequently, collaboration becomes unstable. That is, actors may be hesitant to engage in collaboration or leave a collaboration because they do not perceive a clear benefit in comparison to a non-collaborative scenario.

In this chapter, we address the fourth research question (**Q4**): "How to generate attractive and stable collaboration" by suggesting a collaborative berth allocation approach and propose new row-generation-based algorithms that obtain exact solutions for stable collaborative berth allocation, based on the game theoretic concepts of the core and the nucleolus.

We find the proposed collaborative berth allocation approach leads to significant average cost savings (28.44%) in comparison to the non-collaborative strategy, even after deducting costs related to additional container movements. We further observe that ensuring stable and attractive collaboration incentives (based on the core and nucleolus) results in average savings of 22.97% and 23.92%, which are only slightly below the hypothetical optimum of unconstrained collaboration. Comparing these results to those of a simple cost allocation method from the related literature, we find that the simple method violates the stability criteria of the core (i.e., collaboration leads to increased costs for players) in almost 17 of 33 considered instances. We also see that delays caused in disruption scenarios are reduced when applying the proposed collaborative optimization approaches, and related recovery costs are reduced by 54.98% on average. Finally, our results demonstrate that the nucleolus increases the number of actors with clear collaboration benefits, showcasing an average 49.67% decrease in the variability of individual payoffs in comparison to the core solutions.

These findings extend earlier research on the multiport berth allocation [38, 94] by investigating a new form of collaboration in berth allocation and proposing exact and stable collaboration mechanisms based on the core and the nucleolus. To the best of our knowledge, the proposed row-generation approach is the first of its kind to obtain exact nucleolus solutions for combinatorial optimization problems. Both row-generation algorithms provide general-purpose solution approaches for a large set of related (np-hard) collaborative assignment, routing, or scheduling problems. On the other hand, in terms of practical implications, this study confirms the potential to explore advanced collaboration for efficient and resilient maritime transport and highlights the importance of using stable allocation methods to create strong and lasting collaboration incentives.

In the next chapter, we study the establishment of green maritime corridors where multiple stakeholders are involved collectively to shape a zero-emission future for the maritime shipping industry.

Chapter 6

Network Design and Refueling Station Location Problem for Green Maritime Corridors and Emission Trading

Based on studies of the establishment of stable collaboration in Chapter 5, Chapter 6 answers the research question (**Q5**): "How to design green maritime corridors for achieving a decarbonized or zero-emission future in maritime shipping?". The maritime shipping industry, responsible for 3% of global greenhouse gas emissions, is facing increasing pressure to transition towards decarbonization and ultimately zero emission due to the escalating threat of climate change. This tremendous environmental pressure has inspired the conceptualization of green maritime corridors. Despite initial empirical studies highlighting their potential, the design of these shipping networks and the establishment of necessary refueling stations for alternative fuel ships remain underdeveloped. Furthermore, the impact of the European Emission Trading System (EU ETS), implemented in 2024, on maritime stakeholders and its effectiveness in incentivizing investments in carbon-free or zero-carbon technologies is poorly understood. Therefore, this chapter presents the first optimization approach for designing green maritime corridors.

This chapter is organized as follows. Section 6.1 introduces the research background. Section 6.2 presents a literature review of related works. Section 6.3 describes the optimization problem, while Section 6.4 provides the mathematical model formulations. The experimental results are shown in Section 6.5 by case study. Finally, Section 6.6 summarizes this chapter.

This chapter will be submitted [24][1]

[1] X. Lyu, R. R. Negenborn, F. Schulte (2024), The network design and refueling station location problem for green maritime corridors and emission trading.

6.1 Introduction

To transition towards decarbonization and ultimate zero emission for the maritime sector, the International Maritime Organization (IMO) has established an ambitious target of reducing 50% GHG emissions by 2050 compared with 2008. This urgent need to reduce emissions requires actions of maritime shipping operators. Green maritime corridors can be applied to decarbonize the shipping industry [205], and it is defined as a designated network of shipping routes, ports, and associated infrastructure strategically designed to advocate for maritime shipping practices with low or zero emissions. The primary contributor to emissions stems from the combustion of marine fuels. Thus, such green corridors aim to promote alternative fuels instead of fossil fuels at sea. In 2021, the Clydebank Declaration aims to establish at least six shorter green maritime corridors by the mid-2020s and increase long-distance routes by 2030 [206]. This idea of creating green maritime corridors has recently attracted considerable attention, with governments, ports, and shipping lines announcing the establishment of green corridors jointly as the first step. In addition, the European Emission Trading System (EU ETS) has entered into practice in maritime transportation to accelerate the decarbonization transition. More knowledge is needed on the impact of EU ETS on shipping costs and how this can incentivize stakeholders to invest in carbon-free measures such as creating green maritime corridors.

Several keys are pointed out to the success of any green maritime corridor in [207], and one significance is developing alternative fuel access and port infrastructure. Regarding the potential adoption of methane or LNG, ammonia, and hydrogen in maritime liner shipping, extensive studies in recent years have positioned them as promising alternative fuels for marine fuels to reduce emissions [208, 209]. However, beyond technical feasibility, it is essential to align maritime operations and further plan with the ongoing or near-future energy transition [210]. Specifically, implementing these alternative fuel ships in maritime trade fundamentally requires bunkering infrastructure and corresponding operational capabilities, which are necessary for navigating along designed shipping routes to satisfy the transport requirements between ports. Thus, the design of the shipping network to undertake transport tasks and the investment in bunkering infrastructure to support specific alternative fuel ships are significant for green maritime corridors to succeed from the operational level.

In the literature, researchers primarily focus on governmental policy or technological advancements for conceptualizing green maritime corridors [211]. Certain empirical studies, in particular, actively underscore the pivotal role of developing green corridors in advancing decarbonization within the maritime transportation sector. For example, in [212] and [213], they have scrutinized the viability of green maritime corridors for soybean exportation in Brazil, reporting notable reductions in costs and emissions. Moreover, creating corridor networks is demonstrated to be able to empower individual stakeholders to formulate customized low-carbon or zero-emission solutions [214], as substantiated through a case study within Norway's offshore shipping sector. However, little attention has been paid to the operational modifications required for the successful implementation of green maritime corridors in practical terms. Notably, the design of the shipping network within the corridor and the requisite bunkering stations to support alternative fuel ships within the network still need to be developed. Additionally, implementing green maritime corridors necessitates collaborative efforts from multiple stakeholders, wherein shipping lines, port operators, and governmental bodies are pivotal contributors, jointly working together to create the corridors. Thus, given the implementation of EU ETS, it is vital to estimate emissions fees that need to be paid within different scenarios and compare them with the investment costs for green maritime corridors, providing incentives for shipping operators to join the corridor establishment.

This chapter proposes a general framework to assist the government and companies in designing effective green maritime corridors. Specifically, we first developed a network design and refueling station location problem with green maritime corridors to minimize the overall costs. Our model captures potential synergies across different routes and geographical regions by considering a network of green corridors. Then, we discuss the emissions fees with EU ETS to show the benefits of creating green maritime corridors and the incentives for maritime shipping operators to invest. To the best of our knowledge, this is the first optimization approach to designing green maritime corridors from the operational level and analyzing the impact of EU ETS on incentivizing these carbon-free measures. Our case study reports the green maritime corridor network with the optimized refueling station location. Incorporating EU ETS shows that even with low carbon emission fees, investment in creating corridors is more cost-saving for shipping operators. Overall, this work contributes to energy transition in the maritime domain.

6.2 Literature review

Green maritime corridors are regarded as a relatively new and promising concept for decarbonizing maritime transportation. The overarching purpose is to develop a network of designated maritime shipping routes by running alternative fuel ships to minimize carbon emissions. The establishment of green maritime corridors encompasses several key prerequests. First, alternative fuels in maritime transportation should be applied from a technical perspective. For example, liquefied natural gas (LNG)[215], ammonia [216], and hydrogen [217] have been widely discussed as promising candidates in recent years. Second is the collaboration across the value chain, such as port authorities, shipping companies, cargo owners, and alternative fuel producers/providers. Since COP26, many stakeholders in the maritime shipping industry have been forced to support the development of green corridors, as shown in Figure 6.1. In detail, Table 6.1 concludes the name, announced time, vessel type, alternative fuel, status, and target time of the planned green maritime corridors. Most of the announced green maritime corridors are in their initial partnership stage, and the operational planning problem about how to run alternative ships along the corridor routes still needs to be solved.

Limited research in the literature focuses on the perspective of implementing green maritime corridors, that is, how to commercially operate those alternative ships within the planned corridors. From the optimization modeling standpoint, one closely related study in the literature is the liner shipping network design problem (LSNDP). It is informally defined by [218] as: "given a collection of ports, a fleet of container vessels, and a group of origin-destination demands, construct a set of services for the container vessels such that the overall operational expenses are minimized while ensuring that all demands can be routed through the resulting network, respecting the capacity of vessels". Recently, with the implementation of multiple carbon policies in maritime shipping, many researchers have incorporated the reduction of total CO_2 emissions in LSNDP by integrating various carbon

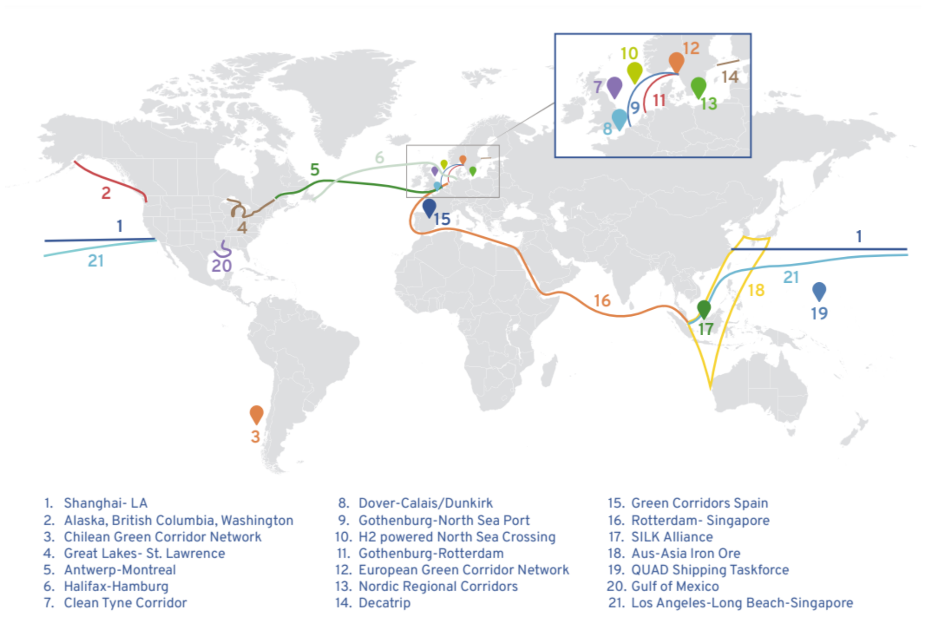


Figure 6.1: Green maritime corridors planned in the world [207]

policies [219, 220]. These studies have shown that these carbon policies can significantly influence the economic performance of LSNDP. From January 2024, EU ETS has been compulsory in maritime transportation. Since its launch in 2005, several studies have discussed the open questions on its potential impact and effectiveness [221]. The investigation by [222] provides support for the positive impact of EU ETS on providing sufficient incentives for specific emission abatement measures. Considering the excellent investment for establishing green maritime corridors, it is important to explore the effects of EU ETS on incentivizing shipping operators to contribute to the construction of alternative fuel ships and refueling infrastructures, thereby promoting the development of green maritime corridors.

Green maritime corridors introduce another dimension to this complex network design problem by integrating clean fuel refueling facilities at ports. Our work aligns closely with existing literature on flow refueling location models (FRLM) that primarily focus on locating alternative fuel facilities for road transport. The model proposed by [223] relates fuel demand to specific routes defined by their origin and destination. They assume that a refueling station can satisfy the demand only if it is located along the route. Such route-based demand representation is more realistic for practical refueling scenarios. Recent advancements have seen the adaptation of the FRLM model for maritime refueling network design, mainly considering LNG as an alternative marine fuel [224]. The study of [225] apples the FRLM model to support decision-makers in building an LNG bunkering network, addressing both truck-to-ship and pipeline-to-ship refueling. Furthermore, a multi-period planning framework is designed by [226] to optimize the refueling barge fleet and routes for ship-to-ship bunkering operations.

However, very limited studies focus on the shipping network and refueling design simultaneously for establishing green maritime corridors from the operational perspective. Given the overview of the current announced green maritime corridors, providing an implementation plan is necessary to promote achieving their target for decarbonization. Therefore, we present the first optimization approach for designing green maritime corridors considering the integrated shipping and fuel network design problem. Based on this model, we compare the economic impacts of EU ETS and further analyze the potential incentives brought by EU ETS for shipping operators to invest in green corridors.

6.3 Problem description

There are multiple open questions for governments and companies to address to establish successful green maritime corridors in the face of many different carbon policies, especially the effect of EU ETS. First, how can the shipping routes of alternative fuel ships be organized so that the cargo transport demands among the involved ports can be satisfied? Second, where (which port) and with which capacity can the bunkering infrastructure be built to support the running of those alternative fuel ships on the established routes? Third, how will EU ETS impact shipping costs and emissions, and can it generate efficient incentives for those ports and shipping lines to motivate them to invest in establishing green corridors?

To answer the above questions, we propose a mathematical model for liner shipping network design with refueling station location problem, in which the shipping routes and bunkering infrastructure construction are planned simultaneously. Based on this model, we obtain answers to the most pressing questions about green maritime corridors in the form of:

(1) A weekly plan for the liner shipping company to operate their alternative fuel ships within the green corridor, consisting of the port-call sequence and bunkering port for ships;

(2) Port investments (which capacity and where?) on the bunkering infrastructure that can support the running of ships on the established routes, including the location (which port) of the refueling stations and their capacities;

(3) An estimation of shipping costs and emission reduction with and without EU ETS, comparing with the investment cost on green maritime corridors and analyzing the incentives for shipping lines and ports.

Based on the definition of the green shipping corridor concept in [205], this section is to design a shipping and fuel network for supporting the establishment of green maritime corridors from the operational level, which consists of zero-emission maritime routes between two or more ports and bunkering infrastructures to refuel alternative-fuel ships at ports. The proposed network design and refueling station location problem supports establishing any green maritime corridor based on some alternative-fuel energy. Even though the problem is relevant for most types of ocean shipping, we present it from the liner shipping perspective.

6.3.1 Assumptions

In this model, we address the optimization of shipping routes that call a predetermined sequence of ports, each pair having a specified transportation demand. The distance between each port pair is known, allowing for calculating sailing times based on a given sailing speed. The routes will be serviced by a selection of alternative fuel vessels, each characterized by specific capacities and associated with defined investment costs, sailing fuel costs, and idle fuel costs when docked at ports. The investment costs for constructing refueling stations of various capacities are also provided, and the costs for integrating zero-emission technologies into the refueling infrastructure are already included.

A critical assumption in our model is that a single type of vessel capacity is selected for each route, ensuring uniformity in vessel size for all departures from any port. This assumption is grounded in practical considerations to maintain realistic and consistent route planning. We aim to identify the optimal vessel routing and refueling station capacities that minimize total costs while meeting transportation demands.

6.3.2 Problem definition

At the strategic planning level, it is imperative to identify optimal locations for refueling stations that can support the operation of alternative-fueled ships. Given the substantial capital investment required for refueling infrastructure, making informed strategic decisions is crucial. At the tactical planning level, the design of the shipping network must be undertaken. This involves determining ship routes, which consist of the sequence of port visits by the fleet, and assigning ships to these routes. During the operational stage of transitioning from traditional routes to green corridors, carriers must decide which cargo to accept or reject and which paths to use for serving the selected cargo, a challenge commonly known in the literature as the cargo-routing problem.

Decisions at these various levels are interdependent. Strategic-level decisions provide overarching guidelines for tactical and operational decisions, while cost and revenue data generated during operations offer critical feedback for refining higher-level strategies. In response to these interdependencies, we propose an integrated model for network design that incorporates refueling station location and addresses the cargo routing problem for each alternative-fueled ship. Specifically, we tackle the LSNDP by organizing alternative fuel ships to support decision-making for planned green maritime corridors. Our formulation simultaneously addresses ship scheduling and cargo routing within the green corridor, with particular emphasis on the refueling station location problem to ensure the effective operation of the green shipping network.

Table 6.1: Overview of the planned green maritime corridors.

Corridor name	Announced time	Vessel type	Alternative fuel	Status	Target time
Oslo-Rotterdam	October, 2023	Container	Hydrogen	Announcement	By 2030
Halifax-Hamburg	September, 2022	Unknown	Methanol, Hydrogen, Ammonia	Announcement	TBD
Rotterdam-Singapore	August, 2022	Container	Methanol, Hydrogen, Ammonia	Conducting feasibility assessment	By 2027
FIN-EST	October, 2023	Vehicle carrier/roro, ferry	Unknown	Announcement	TBD
Antwerp-Montreal	April, 2022	Container, bulk carrier	Unknown	Announcement	TBD
European green corridors	March 2022	Unknown	Unknown	Pre-feasibility assessment conducted	TBD
US-UK	November, 2022	Unknown	Unknown	Announcement	TBD
Canada-US Great Lakes-St lawrence	April, 2022	Unknown	Methanol, Advanced biofuel, Electric	Announcement	TBD
Pacific Northweast to Alaska	May, 2022	Cruise	Unknown	Conducing feasibility assessement	TBD
Republic of Korea-United States	November, 2022	Unknown	Methanol	Pre-feasibility assessment conducted	by 2050
LA-Nagoya	June 2023	Container	Unknown	Announcement	TBD
LA-Long Beach-Singapore	November, 2022	Unknown	Unknown	Conducting feasibility assessment	TBD
LA-Long Beach-Shanghai	January, 2022	Container	Unknown	Developing implementation plan	By 2030
US-Fiji-Pacific blue shipping	March, 2023	Unknown	Unknown	Announcement	TBD
SILK Alliance corridor network	May, 2022	Container	Unknown	Implementation plan developed	TBD
Singapore-Australia	June, 2023	Unknown	Unknown	Conducting pre-feasibility assessment	TBD
Australia-New zealand	-	Unknown	Unknown	Conducting pre-feasibility assessment	TBD
Western Australia-North Asia iron ore	April, 2022	Bulk carrier	Ammonia	Developing implementation plan	TBD
Chile cu-concentrate corridor	-	Bulk carrier	Ammonia	Conducting feasibility assessment	TBD
Chile piscocultura corridor	-	Unknown	Hydrogen	Conducting feasibility assessment	TBD
South Africa-Europe iron ore	March, 2023	Bulk carrier	Ammonia	Conducting pre-feasibility assessment	TBD

Source: compiled using information from https://mission-innovation.net/missions/shipping/green-shipping-corridors/route-tracker/.

6.4 Mathematical formulation

6.4.1 Notation

All the notations used in the formulation are listed in Table 6.2.

Table 6.2: Notation of sets, parameters, and decision variables used in Chapter 6

Notation	Explanation
Sets	
V	Set of all vertex on graph $G=(V,E)$
E_g	Set of ground edges on graph $G=(V,E)$
E_v	Set of voyage edges on graph $G=(V,E)$
E_f	Set of fictitious edges on graph $G=(V,E)$
E	Set of all edges on graph $G=(V,E)$, $E=E_g\cup E_v\cup E_f$
R	Set of routes operated by the involved carriers
P	Set of ports where refueling station can be built
T	Set of vessel types (different capacity)
C	Set of refueling station capacity at ports
W	Set of all index triplets (o,d,i) with o, d, i, representing origin, destination, and day of the week, respectively
R_e	Set of routes using arc $e\in E$
P_e^r	Set of ports that can refuel arc e on route r, $e\in E_v$
E_v^{IN}	Set of incoming edges into vertex v
E_v^{OUT}	Set of out-going edges from vertex v
Parameters	
$R^{(o,d,i)}$	Unit revenues (\$/TEU) by satisfying the demand of $(o,d,i)\in W$
c_t^{ι}	Fixed cost of investing one vessel of type $t\in T$
c_{pc}^{ω}	Fixed cost of investing and operating one refueling station with capacity c at port p
c_{tr}^{θ}	Weekly running cost for one vessel of type $t\in T$ on route $r\in R$
c_e^{κ}	Costs of shipping a TEU cargo on edge e or costs of storing a TEU of cargo at port
h_t	Fuel consumption (tons per day) for vessels of type $t\in T$ when idle at the port
g_t	Fuel consumption (tons per day) for vessels of type $t\in T$ during sailing voyage
$D^{(o,d,i)}$	Demand quantities (in TEUs) from port o to port d on day i, $(o,d,i)\in W$
$d_e, e=(v,u)$	The number of days it takes on edge e from vertex v to vertex u
N_r	(Minimal) Number of ships to serve route $r\in R$
S_r	Sailing time (days) of route $r\in R$
I_r	Idle time at port of route $r\in R$
L_p	(Maximal) Refueling capacity that port $p\in P$ can provide
λ_t	Capacity (in TEUs) for a vessel of type $t\in T$
ρ	Fuel price $(/ton)$
ϕ	(Minimal) Number of routes to choose (invest) in the corridor
Decision variables	
$q_e^{(o,d,i)}$	The quantity of containers demands (in TEUs) allocated to edge $e\in E$
x_r	Binary, equal to 1 if route $r\in R$ is selected, and 0 otherwise
y_{rp}^t	Binary, equal to 1 if ships of type $t\in T$ on route $r\in R$ choose to refuel at port $p\in P$
α_{pc}	Binary, equal to 1 if the refueling station with capacity c is built at port p
m_{tr}	Number of vessels of type $t\in T$ assigned to route $r\in R$

6.4.2 Modeling approach

We define a triplet (o,d,i) to represent a particular demand commodity transport, characterized by the origin port o, the destination port d, and the day i of the week when the supply is available at port o. Given that, generally, no route visits more than one port in one day, and each port is called at least once a week, we consider days as our time units and one week as our planning horizon. We formulate our model based on a directed space-time network $G=(V,E)$ with vertex set V and edge set E, similar as described in [227]. Each vertex $v \in V$ represents a port $p \in P$ on the day of the week $i \in \{1,2,3,4,5,6,7\}$, denoted by v_{pi} or v depending on the exposition ease. We define three types of edges in the network $G=(V,E)$. First, we construct voyage edges E_v to represent the movement of ships from one port to another; Second, we create ground edges E_g to show the overnight staying of ships at a port; Third, we also construct fictitious edges E_f for all demands. That is, $E = E_v \cup E_g \cup E_f$.

Figure 6.2 illustrates one shipping route in a space-time network with four ports, in which two ports are invested to provide refueling services for alternative fuel ships. The length of the edge represents $d_e(v,u)$ days it takes for a ship movement on edge $e=(v,u)$, denoted by d_e for simplicity. Correspondingly, $d_e = 1$ for $e \in E_g$ and $d_e = 0$ for $e \in E_f$. As shown in Figure 6.2, serving such a shipping route with the green corridor necessitates various variable and fixed costs. In our model, we consider four types of costs. First, c_t^{ι} is the cost for each type $t \in T$ of alternative fuel ship invested by shipping companies. Second, c_{pc}^{ω} is the cost of investing and operating a refueling station with capacity $c \in C$ at port $p \in P$. Third, c_{tr}^{θ} represents the weekly running costs incurred by vessels in operation, and fourth, c_e^{κ} reflects the variable cost of cargo movements. In detail, c_e^{κ} for $e \in E_v$ represents the cost of shipping a TEU cargo on voyage edge, and c_e^{κ} for $e \in E_g$ denotes the cost of holding a TEU cargo at the port. The relevant costs are zero for all fictitious edge $e \in E_f$. The route set R contains all the routes operated by the involved carriers that N_r can satisfy the number of ships required to maintain a weekly port-call frequency, which can be shown as a sequence of vertices from vertex v_1 to v_r or edges e_1 to e_{r-1}, that is, $r=[v_1,v_2,...v_r]$ or $r=[e_1,e_2,...e_{r-1}]$.

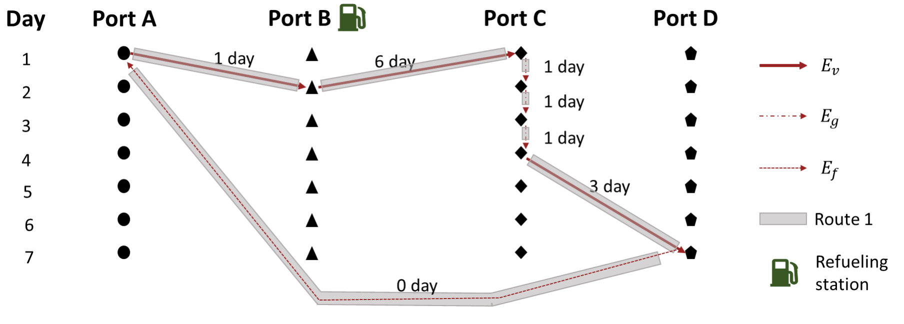


Figure 6.2: Illustration of a shipping route in a space-time network with four ports

6.4.3 Formulations

Based on the above notations, we develop our formulation as follows:

$$\begin{aligned}\min \quad & \sum_{t\in T}\sum_{r\in R} c_t^{\iota} m_{tr} + \sum_{c\in C}\sum_{p\in P} c_{pc}^{\omega}\alpha_{pc} + \sum_{t\in T}\sum_{r\in R} c_{tr}^{\theta} m_{tr} \\ & + \sum_{t\in T}\sum_{r\in R} \rho x_r (S_r g_t + I_r h_t) + \sum_{(o,d,i)\in W}\sum_{e\in E_g\cup E_v} c_e^{\kappa} q_e^{(o,d,i)} \\ & - \sum_{(o,d,i)\in W}\sum_{j=1}^{j=7} R^{(o,d,i)} q_{(v_{dj},v_{oi})}^{(o,d,i)}\end{aligned} \tag{6.1}$$

Subject to:

$$\sum_{e\in E_v^{IN}} q_e^{(o,d,i)} - \sum_{e\in E_v^{OUT}} q_e^{(o,d,i)} = 0 \quad \forall v\in V, (o,d,i)\in W \tag{6.2}$$

$$\sum_{(o,d,i)\in W} q_e^{(o,d,i)} - \sum_{r\in R_e}\sum_{t\in T} \lambda_t m_{tr} \le 0 \quad \forall e\in E_v \tag{6.3}$$

$$\sum_{j=1}^{j=7} q_{(v_{dj},v_{oi})}^{(o,d,i)} \le D^{(o,d,i)} \quad \forall (o,d,i)\in W \tag{6.4}$$

$$\sum_{t\in T}\sum_{r\in R_e}\Big(\sum_{e\in E_v} g_t d_e y_{rp}^t + \sum_{e\in E_g} h_t d_e y_{rp}^t\Big) \le \sum_{c\in C} c\alpha_{pc} \quad \forall p\in P \tag{6.5}$$

$$\sum_{c\in C} c\alpha_{pc} \le L_p \quad \forall p\in P \tag{6.6}$$

$$\sum_{p\in P}\sum_{c\in C} \alpha_{pc} \le 1 \tag{6.7}$$

$$\sum_{p\in P} y_{rp}^t = m_{tr} \quad \forall t\in T, r\in R \tag{6.8}$$

$$N_r x_r \le \sum_{t\in T} m_{tr} \quad \forall r\in R \tag{6.9}$$

$$m_{tr} \le M x_r \quad \forall t\in T, r\in R \tag{6.10}$$

$$m_{tr} \ge x_r \quad \forall t\in T, r\in R \tag{6.11}$$

$$\sum_{r\in R} x_r \ge \phi \quad \forall t\in T, r\in R \tag{6.12}$$

$$q_e^{(o,d,i)} \ge 0 \quad \forall (o,d,i)\in W, e\in E \tag{6.13}$$

$$m_{tr} \ge 0 \quad \forall t\in T, r\in R \tag{6.14}$$

$$y_{rp}^t \in \{0,1\} \quad \forall r\in R, p\in P, t\in T \tag{6.15}$$

$$\alpha_{pc} \in \{0,1\} \quad \forall p\in P, c\in C \tag{6.16}$$

$$x_r \in \{0,1\} \quad \forall r\in R \tag{6.17}$$

The objective function (6.1) minimizes the total system costs within the green maritime corridor. The first two terms capture the investment costs of vessels and refueling stations, respectively. The third term represents the weekly costs incurred by operating those alternative fuel ships within the green corridor. The fourth term obtains the fuel costs including consumption during both the sailing in the sea and idling at the port. The fifth term denotes the costs of shipping cargoes along the routes connecting various origin and destination pairs. The last term computes the revenue generated from fulfilling cargo transport demands, compensating system costs.

Constraint (6.2) ensures commodity flow balance at each vertex of the space-time network. For each commodity $(o,d,i) \in W$, the total flow into each vertex v must be equal to the flow out of it. Constraint (6.3) is an edge capacity constraint, which ensures that the total flow on a voyage edge should be within the capacity of all types of vessels operated on that edge. Constraint (6.4) guarantees that the total flow of a given commodity from its origin port to the destination port cannot exceed the demand at the destination port. Constraint (6.5) ensures that the capacity of the refueling station must satisfy the alternative fuel demands of all vessels required from this refueling station. We assume that a ship would be fueled up to its capacity and thus, the required quantity of alternative fuels at the refueling station is equal to the days travelled multiplied by the fuel consumption rate. Constraint (6.6) requires that the fuel capacity of the refueling station is less than or equal to the maximal alternative fuels that the port can invest. Constraint (6.7) states that only one capacity can be chosen by a port to build the refueling station. Constranit (6.8) ensures that all ships running the route can be refueled at the port. Constraint (6.9) states all types of vessels assigned to each route should not be less than the minimal number of vessels required by this route. Constraints (6.10-6.11) define the internal relationship between two variables m_{tr} and x_r, representing that the vessels can only be assigned to the route being selected to operate within the green corridor. Constraint (6.13) satisfies the requirements on the minimal number of routes to invest within the corridors. Finally, constraints (6.14-6.17) denote the properties of all decision variables.

6.5 Case study

We consider the Northern European & Baltic Green Corridor project initiated in December 2021. As shown in Figure 6.3, the project involves collaborative efforts involving pioneering ports in the Baltic Sea region: the Ports of Gdynia, Roenne, Rotterdam, and Tallinn, as well as the Hamburg Port Authority. This initiative was undertaken in partnership with the Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, while it is still at the initial pre-feasibility stage. Our model aims to provide decision support on establishing green shipping corridors from the operational level and drive the maritime industry to zero emission in the future.

In the following, we describe the data input used in creating the Northern European Corridors in Section 6.5.1. We follow that by presenting the shipping network and bunkering design suggested by our model for creating the green corridor in Section 6.5.2. Next, we study the potential benefits of carbon dioxide emissions with and without considering EU ETS in Section 6.5.3.

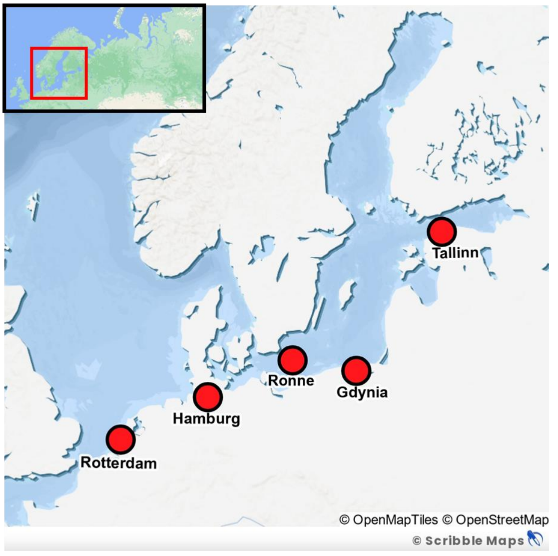


Figure 6.3: Map of Green Corridor in Northern Europe and the Baltic Sea

6.5.1 Input data

Costs relevant to apply alternative-fuel vessels are shown in Table 6.3. In the Northern European & Baltic green maritime corridor, four liner shipping routes are under consideration, including Route 1: Port of Rotterdam → Port of Hamburg → Port of Rønne → Port of Rotterdam, Route 2: Port of Rotterdam → Port of Hamburg → Port of Rønne → Port of Gdynia → Port of Tallinn → Port of Rotterdam, Route 3: Port of Hamburg → Port of Tallinn → Port of Gdynia → Port of Hamburg, and Route 4: Port of Rotterdam → Port of Rønne → Port of Tallinn → Port of Gdynia → Port of Rotterdam. While currently serviced by conventional vessels, there are plans to introduce alternative-fueled vessels in the coming years to establish environmentally sustainable corridors. We obtain the distance between ports from the website https://www.routescanner.com/ and calculate the days it takes by vessel speed of 18 knots.

Table 6.3: The parameters values for vessel types utilized in experiments [228]

Parameter	**Unit**	**Value**	
		Type A	Type B
Capacity	TEU	900	1500
Operating speed	Knot	18	18
Fixed vessel investment costs c_t^1	10^3 \$	48.3	60.4
Fuel consumption at sea g_t	Ton/Day	75	90
Fuel consumption in port h_t	Ton/Day	5	5
Operating costs (to calculate c_{tr}^{θ})	10^3\$/Day	$U[8,10]$	$U[14,16]$

Table 6.4: The route-relevant parameters

Parameter	Unit	Route 1	Route 2	Route 3	Route 4
Number of ships N_r	Ship	1	2	1	2
Sailing time at sea S_r	Day	2	7	6	8
Idle time in port I_r	Day	4	3	1	1

According to [229] and [230], port investment costs of bunkering structure are generated randomly from 300 $10^3\$/Ton$ to 700 $10^3\$/Ton$, with the capacity of bunkering station in 10000, 12000, 15000, 18000 tons, respectively. The OD demands are generated according to history data published by Maersk shipping line.

The total amount of CO_2 emissions by the traditional fuel vessels by multiplying a factor of converting fuel cost to CO_2 defined by [231]:

$$E_f^{CO_2} = 3.17,$$

representing the amount of tons of CO_2 emissions by burning per ton of traditional fuel.

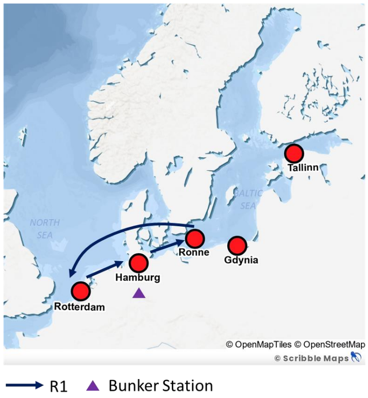
6.5.2 Green maritime corridor design

Table 6.5 shows the proposed corridor design for the Northern European Green Maritime Corridor under different values of ϕ representing the limitation of routes number to invest. Regarding the implementation from the operational perspective, several decisions are provided by our model, including alternative-fueled vessel deployment, shipping network design, and bunkering station investment. In detail, we report the selected routes, bunkering station location and capacity, alternative-fueled ship types and numbers, reduced CO_2 emissions, total corridor costs, and the cost for unit reduction of CO_2 emissions. We observe that each type of alternative fuel ship is deployed on each selected route, and the Port of Hamburg and the Port of Rotterdam are the two most potential ports where bunkering stations are located. Figure 6.4 visually represents the Northern European Creen Maritime Corridor.

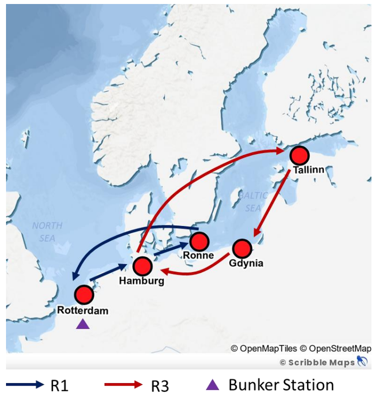
Table 6.5: Results of Northern European corridor network design based on our model

	Selected Route	Bunker Station		Alternative-fueled Ship		Reduced CO_2 Emissions (ton)	Total Corridor Costs (10^3\$)	Unit Cost of CO_2 Reduction (10^3\$/ton)
		Location	Capacity (ton)	Type	Number			
$\phi = 1$	R1	Hamburg	10000	A B	1 1	912.96	27735.50	30.38
$\phi = 2$	R1, R3	Rotterdam	12000	A B	2 2	1210.94	32255.60	26.64
$\phi = 3$	R1, R2, R3	Hamburg	12000	A B	3 3	1965.40	30553.60	15.55
$\phi = 4$	R1, R2, R3, R4	Hamburg	15000	A B	4 4	2288.74	32203.60	14.07

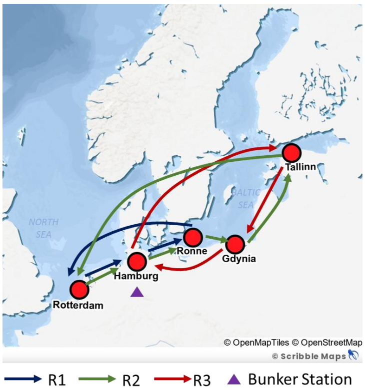
Next, in Figure 6.5, we compare the total reduction of CO_2 emissions and the cost of unit CO_2 reduction under the different sizes of the network (represented by ϕ). It is shown that the total reduction of CO_2 emissions increases with investing more routes into the green corridors, and the unit cost for emission reduction decreases simultaneously.



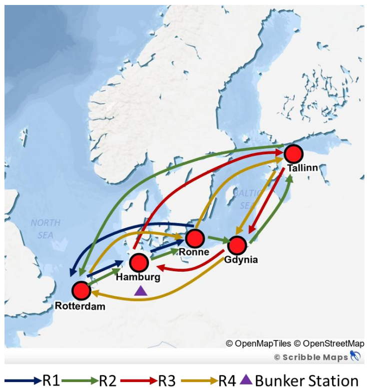
(a) $\phi = 1$



(b) $\phi = 2$



(c) $\phi = 3$



(d) $\phi = 4$

Figure 6.4: Northern European & Baltic green maritime corridor

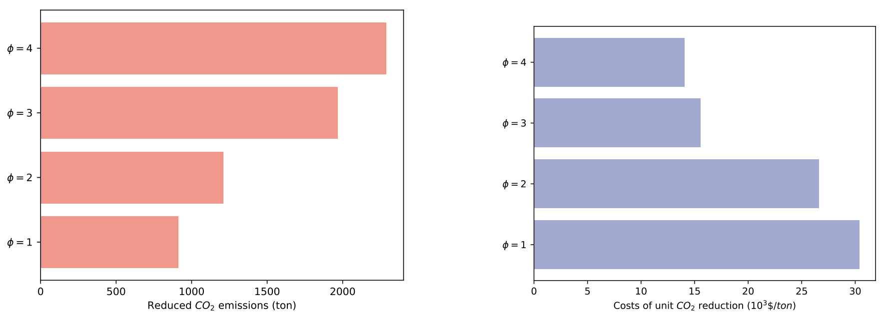
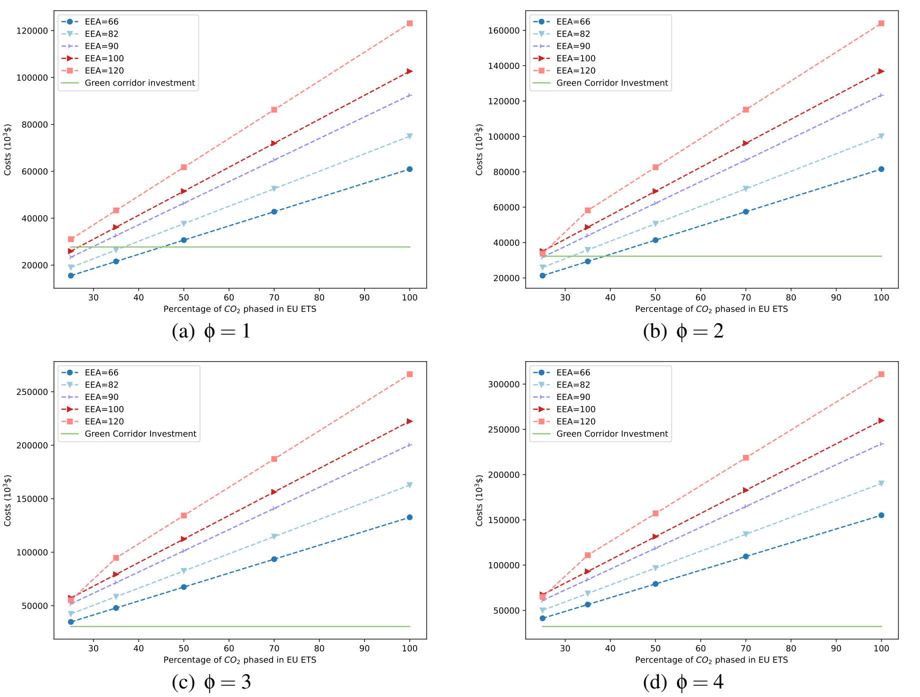


Figure 6.5: Impact of network size on CO_2 emissions

6.5.3 Cost comparison with consideration of EU ETS

Maritime transportation was announced to be included into the European Union Emission Trading System (EU ETS) that entered into force on January 1, 2024. The EU ETS comes as a result of the increasing regulatory landscape imposed by the IMO, which will directly impact the EU maritime shipping market. The high carbon tax fee provides potential incentives for creating green maritime corridors. Therefore, we compare the payment on carbon emissions under the regulation of EU ETS with the investment on alternative-fueled ships and bunkering stations, implicating the attraction of creating green maritime corridors.

One emission allowance in EU ETS, referred to as EEA in our paper, represents one ton of CO_2 equivalent. For example, $EEA = 66$ means one ton of $C0_2$ emissions need to pay for 66$ for operators. There is a planned stage to count all CO_2 emissions into EU ETS gradually, thus, in Figure 6.6, we compare the CO_2 emission costs under different EEA first and under different cases on 25%, 35%, 50%, 70%, 100% percentage of CO_2 emissions phrased-in EU ETS. From Figure 6.6(c) and Figure 6.6(d), we observed that the investment on establishing at least three routes is attractive for operators under EU ETS. Moreover, the continuously rising prices of the carbon allowances and the expected inclusion of shipping into the EU ETS has created a need to understand the financial exposure related to shipping for operators. Furthermore, as shown in Figure 6.6(a) and Figure 6.6(b), even with the low EEA, the larger percentage of CO_2 phrased-in EU ETS, the carbon tax payment increased dramatically to exceed the investment on green corridors, which provides sufficient incentives for operators to take specific measures to join establishing green maritime corridors.



(a) $\phi = 1$ (b) $\phi = 2$

(c) $\phi = 3$ (d) $\phi = 4$

Figure 6.6: Comparison with consideration of EU ETS

6.6 Conclusions

This chapter answers the research question (**Q5**): "How to design green maritime corridors for achieving a decarbonized or zero-emission future in maritime shipping?". In this chapter, we propose a network design and refueling station location problem for establishing green maritime corridors from the implementation perspective, where the sequence of port calls, the optimal number of vessels to deploy in the service, and the optimal refueling station location and capacity are included in the decisions. The proposed model minimizes the total costs of running alternative fuel ships within the green corridors.

We apply the model to the announced European Green Maritime Corridors. The results show the scale of economy on the cost of CO_2 emission reduction, that is, from $30.38(10^3\$/ton)$ with running on one route to $14.07(10^3\$/ton)$ with running on four routes in the corridor. Furthermore, we discuss the impact of EU ETS on shipping costs because of carbon emissions with different emission allowances. Even with a low emission allowance, the carbon emission payment caused by EU ETS can dramatically exceed the investment cost of establishing green maritime corridors. Therefore, the EU ETS can provide sufficient incentives for shipping operators and stakeholders to contribute to the design of green corridors. In future work, the proposed model can be tested on different cases of the announced green corridors, and more types of alternative fuels should also be considered in different corridors.

Chapter 7

Conclusions and Future Research

This thesis investigates the collaborative strategies to enhance maritime and port operations toward resilience and decarbonization from an OR perspective. Based on the identified two main types of collaboration, horizontal and vertical collaboration approaches are examined and studied, respectively, to show the performance of the proposed collaborative schemes. A general cost allocation mechanism based on cooperative game theory is developed to establish an attractive and stable collaboration. Besides, we propose the optimization model for establishing green maritime corridors based on collaboration among multiple stakeholders, promoting maritime shipping towards decarbonization or even zero-emission from the operational perspective.

This last chapter concludes the thesis. The research questions in Chapter 1 are answered in Section 7.1. Section 7.2 presents the managerial insights for managers and policy-makers based on the results of this thesis. Finally, Section 7.3 provides future research directions.

7.1 Research questions

This section answers the five sub-reasearch questions and the main research questions presented in Chapter 1. The main research question is answered by addressing five sub-research questions through Chapters 2-6.

7.1.1 Sub-research questions

We summarize answers to these sub-questions as follows:

1. *What are the characteristics and key challenges of collaborative maritime and port operations?*

   In Chapter 2, we identify three key collaboration types (horizontal, vertical, and horizontal and vertical collaboration) consisting of three main stakeholders (shipping lines, port or terminal operators, and other logistics service providers), analyzing the related collaborative systems. In this way, we bring the fragmented problems together and thus identify research gaps to promote collaborative strategies for maritime transport for higher efficiency, resilience, and decarbonization.

2. *How do OR methodologies contribute to the decision-making of collaborative systems in maritime and port operations?*

   By Chapter 2, we made a dedicated literature survey on collaborative maritime and port operations from the OR perspective. In the literature survey, we specifically strengthen the OR contributions (e.g., innovative models, algorithms, and mechanisms).

   Reviews on vertical and horizontal collaboration in maritime and port operations highlight the potential for developing collaborative maritime shipping systems. Technological advancements, like real-time information sharing, call for innovative business frameworks and new models even for traditional problems. We find that most existing studies assume that the collaboration has already been established, ignoring the incentives and stability of the collaboration. Thus, other than collaborative planning models, it is important to provide methods for incentivizing individual members to join the partnerships.

3. *How does collaboration work as a means for efficient and resilient port operations?*

   In Chapter 3, based on horizontal collaboration, a collaborative berth planning model is proposed in response to disruption, which focuses on the collaboration among terminals and transshipment connections between vessels, as concluded in Table 2.3. The results from the performed computational experiments of this chapter, considering multiple scenarios with disruptive events, show consistent cost savings up to 40% and average cost savings in the range of 11.43%-23% for the suggested collaborative strategy in terms of costs for the terminal operators. In Chapter 4, based on vertical collaboration, we develop a hybrid berth allocation optimization model dedicated to bulk ports, as concluded in Table 2.1. In addition to considering the handling characteristics of bulk ports, unavailability and stock-level constraints are also incorporated into the integrated decision-making process. The experimental results show that integrating unavailability constraints into the BAP model can significantly decrease total demurrage fees.

4. *How to generate attractive and stable collaboration?*

   Existing collaborative planning models often disregard the requirements and incentives of stakeholders or simply solve idealized small instances. Thus, in Chapter 5, we design attractive and stable collaboration mechanisms by allocating the coalitional benefits fairly and reasonably among individuals, as concluded in Table 2.4. In detail, we first define the collaborative berth allocation problem and propose a mixed integer linear programming (MILP) model; then, we adopt the core and the nucleolus concepts from cooperative game theory to allocate the coalitional costs so stakeholders have stable incentives to collaborate. To obtain solutions for realistic instance sizes, we propose two exact row-generation-based core and nucleolus algorithms that are versatile and can be used for various combinatorial optimization problems. The results of our numerical experiments calculating the core and the nucleolus ensure that the cost allocated to individual terminals does not exceed their stand-alone costs, on average, achieving savings of 22.97% and 23.92% for individual costs, respectively, thereby maintaining stable collaboration incentives. That is, ensuring stable and attractive collaboration incentives (based on the core and nucleolus) results in average savings that are only about 5 percentage points lower than the hypothetical collaboration optimum (28.44%).

5. *How to design green maritime corridors for achieving a decarbonized or zero-emission future in maritime shipping?*

   In Chapter 6, we propose an optimization model to minimize the overall costs by establishing green maritime corridors, with and without an emission trading system such as EU ETS. A further comparison between the emission tax costs and investment costs on green corridors is presented. The results show the scale of economy on the cost of CO_2 emission reduction, that is, from $30.38(10^3\$/ton)$ with running on one route to $14.07(10^3\$/ton)$ with running on four routes in the corridor. Cost comparisons with the EU ETS, we find that even with a low emission allowance, the carbon emission payment caused by EU ETS can dramatically exceed the investment cost of establishing green maritime corridors. Therefore, the EU ETS provides sufficient incentives for shipping operators and stakeholders to join green corridors.

7.1.2 Main research question

The main research question is: *How can collaborative strategies contribute to maritime and port operations towards a higher level of efficiency, resilience, and decarbonization?*

We begin with a comprehensive literature survey on collaboration in maritime and port operations, classifying the development of collaborative strategies. Following this review, we explore new decision-making optimization opportunities in both horizontal and vertical collaboration. For horizontal collaboration, we propose an innovative berth planning model based on terminal collaboration, which accounts for practical disruptions to enhance resilience. In the context of vertical collaboration, we investigate an integrated berth planning approach for bulk terminals. Experimental results emphasize the necessity for bulk terminal managers to incorporate constraints such as unavailability and stock levels into their decision-making processes to ensure operational stability and minimize costs. From a practical standpoint, effective incentive schemes for forming collaboration is crucial. To address this, we propose exact and stable collaboration mechanisms using the core and the nucleolus and develop two exact row-generation-based algorithms to solve realistic instance sizes, offering general-purpose solutions for a wide range of related NP-hard collaborative assignment, routing, or scheduling problems. The results of the proposed cost-allocation algorithms underscore the importance of stable allocation methods to foster lasting collaboration. In terms of decarbonization, the concept of green maritime corridors is promising yet still in its conceptual stage. To support implementation, we present the first optimization approach for designing green maritime corridors. We compare the costs of investing in green corridors with EU ETS costs, demonstrating sufficient incentives for shipping stakeholders to participate in establishing green maritime corridors.

Table 7.1 shows the attributes of the collaboration in maritime and port operations that have been addressed in each chapter of this thesis. The findings of this thesis in Chapters 3, 4, and 6 provide decision support for different collaborative systems in maritime and port operations. Specifically, the proposed cost allocation mechanism based on cooperative game theory in Chapter 5 gives general-purpose support for incentivizing partners to form collaboration and maintain stability in practice.

Table 7.1: Features of collaboration in maritime and port operations in Chapters 3-6.

	Collaboration type	Involved stakeholders			Decision problem	Objective			Collaboration incentives/stability
		TO	SL	LP		E	R	D	
Chapter 3	H	✓			Berth allocation problem for container terminals	✓	✓		NO
Chapter 4	V	✓	✓	✓	Berth allocation problem for bulk terminals	✓			NO
Chapter 5	H	✓			Berth allocation problem & shared cost allocations	✓	✓		YES
Chapter 6	H & V	✓	✓		Green maritime corridor & refueling design	✓		✓	NO

H:horizontal; V:vertical; TO:terminal operators; SL:shipping lines; LS: logistics providers; E:efficiency; R:resilience; D:decarbonization.

7.2 Managerial insights

The results of this thesis provide managerial insights for managers and policy-makers to enhance the performance of maritime and port operations. The main managerial insights are listed as follows:

1. Ports with multiple terminals are highly recommended to apply the collaborative berth planning approach proposed in Chapter 3 to decide when and where the calling vessels should be berthed based on sharing the resources of berths and quay cranes among terminals. In particular, for handling disruptions in ports, the transshipment connections between feeder and mother vessels should also be considered when rescheduling the berthing plan.

2. Bulk terminal operators are expected to benefit from the integrated berthing strategy proposed in Chapter 4 by incorporating more practical factors (e.g., unavailability of berths and the stock level).

3. The proposed berth allocation based on inter-terminal collaboration in Chapter 5 exhibits significant cost reduction potential for terminal operators in both conventional and disruptive scenarios.

4. The proposed general-purpose row-generation method to obtain the core and nucleolus cost (or profit) allocations for the combinatorial optimization problem in Chapter 5 can help to generate stable and attractive collaboration incentives.

5. With the developed optimization model of network design and refueling station location problem in Chapter 6, the shipping industry can obtain decision support to establish green maritime corridors from the implementation level.

7.3 Future research directions

7.3.1 Research limitations of this thesis and improvement directions

There are still challenges for the methodological framework and its application proposed in this thesis. These challenges also indicate some future research directions.

1. In Chapter 5, we proposed a horizontal berth allocation planning model based on terminal collaboration, considering the extra costs of exchanging containers between terminals. However, it does not explicitly consider the corresponding emission and disruption costs on port-hinterland operations caused by these extra movements. In reality, the feasibility of these container moving can significantly impact the achievement of the collaborative model. Therefore, in the future, the berth planning model combining the horizontal collaboration among terminals and the vertical cooperation between terminal operators and hinterland logistics service providers is worth further exploring for higher performance on cost savings (or profit improvement).

2. In Chapter 4, we tested the performance of an integrated berthing strategy for bulk terminals in a small instance size with three terminals and up to 18 vessels by the commercial software CPLEX. However, our model can not solve large-scale instances using CPLEX within a reasonable computing time. Future work should develop some algorithms for testing larger-scaled instances.

3. In Chapter 5, the proposed two cost allocation algorithms get over the restriction of the number of players. However, they are restricted to the speed of getting the optimal value of the optimization model of berth allocation. Furthermore, our cost allocation algorithms require the exact solutions of the optimized berth allocation model as input. Thus, developing effective exact algorithms to speed up the computation of the berth allocation model has great potential for applying the cost allocation methods to larger instance sizes.

4. Chapter 6 tested the network design and refueling station location model based on the intra-Europe network–European Green Maritime Corridors with five ports and four shipping routes. Future research should further test the performance of the proposed model in larger and more complex inter-continent networks, such as the Singapore-Rotterdam corridor.

7.3.2 Future research agenda

Several future research agenda in a broader scope are given as follows:

1. *Identifying collaborative settings and establishing optimization techniques*
   Since planning processes based on resource-sharing from multiple stakeholders are more complex than general planning, some studies simplify the constraints in optimization models. However, in the collaborative vehicle routing and network problem, such as vessel scheduling in shipping alliance and truck scheduling for container drayage operation, the results without the assumption of homogeneous fleets of each member, same service frequencies, and deterministic sailing speed on the leg will be

worthy of making the model more in line with practice. Also, some realistic constraints, such as drafts, and tide, physical constraints of port layout, and soft restrictions could be considered in the mathematical modeling under collaboration setting.

2. *Exploring the effective combination of machine learning method with the OR method*
   Many collaborative planning problems in maritime and port operations are combinatorial optimization problems with NP-hard features. Therefore, many researchers rely on heuristics that need to be mathematically well-defined, although computationally time-saving. Moreover, the proposed exact algorithms are confined to the application because most of them are problem-specific. Recently, the Machine Learning (ML) method has been brought to the attention of OR researchers. Thus, a promising research direction is the integration of ML and OR, which takes advantage of the computational simplicity of ML and the mathematical excellence of OR simultaneously. For instance, the CBAP model presented in this thesis is formulated based on the Expected Arrival Time (ETA) of vessels. Enhancing the accuracy of ETA predictions can significantly improve port efficiency, as highlighted by [232]. Given this, exploring berth planning optimization with ETA predictions powered by ML techniques represents a highly promising direction for future research. Such advancements could not only refine the precision of planning but also lead to more streamlined and adaptive port operations.

   Considering the multiple stakeholders involved in the collaboration making decisions based on expectations of others' actions and potential payoffs, on one hand, ML can enhance this by using data-driven models to predict player behavior and choices. On the other hand, ML could be used to learn optimal mechanisms or incentive structures from data. For instance, if terminal operators and shipping companies need to collaborate on berth allocation, ML could identify patterns in their behavior and suggest incentive schemes that lead to optimal cooperation.

3. *Advanced models accounting for uncertainty and flexibility*
   Real-time planning relating to disruptive considerations is interesting. The disruptions of container flows caused by the COVID-19 pandemic have brought maritime researchers and practitioners close attention to disruptive management issues. Thus, dynamic routing and speed optimization are necessary for ocean shipping and port logistics to maximize profits [129] in a highly dynamic environment. Also, the information can be continuously exchanged among the collaborative members due to the advancement of technology. Therefore, we need one-demand planning models to support flexible and real-time collaboration, such as incomplete information sharing and membership change.

4. *Exploring innovative collaboration based on autonomous system*
   Automated technology advancement in hardware (facility) and software (information sharing) proposes new opportunities for freight maritime transportation. Due to a higher level of automation, reduced human involvement opens new collaborative planning problems in autonomous transportation with distinct features. The platooning form (e.g., vessel train and truck platoon) is still in its infancy. For real-world implementation, more practical considerations need to be further explored, such as dealing with the uncertainty of travel time, system sustainability, and network design

upgrading for maximizing the benefits of platooning [117]. Regarding the development of automated container terminals, there is a set of new planning problems accompanying the innovative handling modes based on the coordination of autonomous vehicles.

Bibliography

[1] UNCTAD, Review of maritime transport 2019 (2019).

[2] UNCTAD, Review of maritime transport 2023 (2023).

[3] Ti, Ocean freight rate tracker: Q2 2022, https://www.ti-insight.com/whitepapers/ocean-freight-rate-tracker-q2-2022/, (Accessed: 02-01-2022) (2022).

[4] UNFCCC, The paris agreement, https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement, (Accessed: 01-05-2024) (2015).

[5] F. Cruijssen, M. Cools, W. Dullaert, Horizontal cooperation in logistics: opportunities and impediments, Transportation Research Part E: Logistics and Transportation Review 43 (2) (2007) 129–142.

[6] H. E. Haralambides, The economics of bulk shipping pools, Maritime Policy and Management 23 (3) (1996) 221–237.

[7] A. Moros-Daza, R. Amaya-Mier, C. Paternina-Arboleda, Port community systems: A structured literature review, Transportation Research Part A: Policy and Practice 133 (2020) 27–46.

[8] B. Groothedde, C. Ruijgrok, L. Tavasszy, Towards collaborative, intermodal hub networks: A case study in the fast moving consumer goods market, Transportation Research Part E: Logistics and Transportation Review 41 (6) (2005) 567–583.

[9] T. Ambra, A. Caris, C. Macharis, Towards freight transport system unification: reviewing and combining the advancements in the physical internet and synchromodal transport research, International Journal of Production Research 57 (6) (2019) 1606–1623.

[10] C. Cleophas, C. Cottrill, J. F. Ehmke, K. Tierney, Collaborative urban transportation: Recent advances in theory and practice, European Journal of Operational Research 273 (3) (2019) 801–816.

[11] F. Pomponi, L. Fratocchi, S. R. Tafuri, M. Palumbo, Horizontal collaboration in logistics: a comprehensive framework, Research in Logistics & Production 3 (2013).

[12] M. Soysal, J. M. Bloemhof-Ruwaard, R. Haijema, J. G. van der Vorst, Modeling a green inventory routing problem for perishable products with horizontal collaboration, Computers & Operations Research 89 (2018) 168–182.

[13] J. R. Montoya-Torres, A. Muñoz-Villamizar, C. A. Vega-Mejía, On the impact of collaborative strategies for goods delivery in city logistics, Production Planning & Control 27 (6) (2016) 443–455.

[14] K. Scholten, S. Schilder, The role of collaboration in supply chain resilience, Supply Chain Management: An International Journal 20 (4) (2015) 471–484.

[15] R. Ishfaq, Resilience through flexibility in transportation operations, International Journal of Logistics Research and Applications 15 (4) (2012) 215–229.

[16] L. Chen, X. Zhao, O. Tang, L. Price, S. Zhang, W. Zhu, Supply chain collaboration for sustainability: A literature review and future research agenda, International Journal of Production Economics 194 (2017) 73–87.

[17] Z. Tan, Q. Meng, F. Wang, H.-b. Kuang, Strategic integration of the inland port and shipping service for the ocean carrier, Transportation Research Part E: Logistics and Transportation Review 110 (2018) 90–109.

[18] L. Ascencio, R. González-Ramírez, L. Bearzotti, N. Smith, J. Camacho-Vallejo, A collaborative supply chain management system for a maritime port logistics chain, Journal of applied research and technology 12 (3) (2014) 444–458.

[19] X. Lyu, K. Tierney, F. Schulte, Collaborative maritime and port operations: A literature review and roadmap, Submitted (2024).

[20] M. Gansterer, R. F. Hartl, Shared resources in collaborative vehicle routing, Top 28 (2020) 1–20.

[21] M. Guajardo, M. Rönnqvist, A review on cost allocation methods in collaborative transportation, International transactions in operational research 23 (3) (2016) 371–392.

[22] X. Lyu, R. R. Negenborn, X. Shi, F. Schulte, A collaborative berth planning approach for disruption recovery, IEEE Open Journal of Intelligent Transportation Systems 3 (2022) 153–164.

[23] X. Lyu, F. Schulte, Hybrid berth allocation for bulk ports with unavailability and stock level constraints, in: Proceedings of 13th International Conference on Computational Logistics, Barcelona, Spain, 2022, pp. 3–15.

[24] X. Lyu, R. R. Negenborn, F. Schulte, The network design and refueling station location problem for green maritime corridors and emission trading, To be submitted (2024).

[25] X. Lyu, E. Lalla-Ruiz, F. Schulte, The collaborative berth allocation problem with row-generation algorithms for stable cost allocations, Submitted (2024).

[26] I. Sung, H. Zografakis, P. Nielsen, Multi-lateral ocean voyage optimization for cargo vessels as a decarbonization method, Transportation Research Part D: Transport and Environment 110 (2022) 103407.

[27] J. Mulder, W. van Jaarsveld, R. Dekker, Simultaneous optimization of speed and buffer times with an application to liner shipping, Transportation science 53 (2) (2019) 365–382.

[28] M. A. Dulebenets, Minimizing the total liner shipping route service costs via application of an efficient collaborative agreement, IEEE Transactions on Intelligent Transportation Systems 20 (1) (2018) 123–136.

[29] M. A. Dulebenets, Multi-objective collaborative agreements amongst shipping lines and marine terminal operators for sustainable and environmental-friendly ship schedule design, Journal of Cleaner Production 342 (2022) 130897.

[30] Z. Liu, S. Wang, Y. Du, H. Wang, Supply chain cost minimization by collaboration between liner shipping companies and port operators, Transportation Journal 55 (3) (2016) 296–314.

[31] S. Wang, Z. Liu, X. Qu, Collaborative mechanisms for berth allocation, Advanced Engineering Informatics 29 (3) (2015) 332–338.

[32] H. Wang, S. Wang, Q. Meng, Simultaneous optimization of schedule coordination and cargo allocation for liner container shipping networks, Transportation Research Part E: Logistics and Transportation Review 70 (2014) 261–273.

[33] L. B. Reinhardt, C. E. Plum, D. Pisinger, M. M. Sigurd, G. T. Vial, The liner shipping berth scheduling problem with transit times, Transportation Research Part E: Logistics and Transportation Review 86 (2016) 116–128.

[34] S. Nikghadam, R. Vanga, J. Rezaei, L. Tavasszy, Cooperation between vessel service providers in ports: An impact analysis using simulation for the port of rotterdam, Maritime Transport Research 4 (2023) 100083.

[35] O. Abou Kasm, A. Diabat, M. Bierlaire, Vessel scheduling with pilotage and tugging considerations, Transportation Research Part E: Logistics and Transportation Review 148 (2021) 102231.

[36] X. Zhang, J. Li, Z. Yang, X. Wang, Collaborative optimization for loading operation planning and vessel traffic scheduling in dry bulk ports, Advanced Engineering Informatics 51 (2022) 101489.

[37] M. M. Golias, G. K. Saharidis, M. Boile, S. Theofanis, M. G. Ierapetritou, The berth allocation problem: Optimizing vessel arrival time, Maritime Economics & Logistics 11 (2009) 358–377.

[38] G. Venturini, Ç. Iris, C. A. Kontovas, A. Larsen, The multi-port berth allocation problem with speed optimization and emission considerations, Transportation Research Part D: Transport and Environment 54 (2017) 142–159.

[39] H. Zhu, Integrated containership stowage planning: A methodology for coordinating containership stowage plan and terminal yard operations, Sustainability 14 (20) (2022) 13376.

[40] Ç. Iris, J. Christensen, D. Pacino, S. Ropke, Flexible ship loading problem with transfer vehicle assignment and scheduling, Transportation Research Part B: Methodological 111 (2018) 113–134.

[41] C. Bierwirth, F. Meisel, A survey of berth allocation and quay crane scheduling problems in container terminals, European Journal of Operational Research 202 (3) (2010) 615–627.

[42] J. G. Jin, D.-H. Lee, H. Hu, Tactical berth and yard template design at container transshipment terminals: A column generation based approach, Transportation Research Part E: Logistics and Transportation Review 73 (2015) 168–184.

[43] L. Zhen, D. Zhuge, S. Wang, K. Wang, Integrated berth and yard space allocation under uncertainty, Transportation Research Part B: Methodological 162 (2022) 1–27.

[44] R. T. Cahyono, S. P. Kenaka, B. Jayawardhana, Simultaneous allocation and scheduling of quay cranes, yard cranes, and trucks in dynamical integrated container terminal operations, IEEE Transactions on Intelligent Transportation Systems 23 (7) (2021) 8564–8578.

[45] L. Kong, M. Ji, Z. Gao, Joint optimization of container slot planning and truck scheduling for tandem quay cranes, European Journal of Operational Research 293 (1) (2021) 149–166.

[46] O. Abou Kasm, A. Diabat, J. Y. Chow, Simultaneous operation of next-generation and traditional quay cranes at container terminals, European Journal of Operational Research (2022).

[47] J. Shouwen, L. Di, C. Zhengrong, G. Dong, Integrated scheduling in automated container terminals considering agv conflict-free routing, Transportation Letters 13 (7) (2021) 501–513.

[48] J. Luo, Y. Wu, A. B. Mendes, Modelling of integrated vehicle scheduling and container storage problems in unloading process at an automated container terminal, Computers & Industrial Engineering 94 (2016) 32–44.

[49] H. Li, J. Peng, X. Wang, J. Wan, Integrated resource assignment and scheduling optimization with limited critical equipment constraints at an automated container terminal, IEEE Transactions on Intelligent Transportation Systems 22 (12) (2020) 7607–7618.

[50] Y. Chang, X. Zhu, B. Yan, L. Wang, Integrated scheduling of handling operations in railway container terminals, Transportation Letters 11 (7) (2019) 402–412.

[51] Q. Hu, F. Corman, B. Wiegmans, G. Lodewijks, A tabu search algorithm to solve the integrated planning of container on an inter-terminal network connected with a hinterland rail network, Transportation Research Part C: Emerging Technologies 91 (2018) 15–36.

[52] D.-H. Lee, J. G. Jin, Feeder vessel management at container transshipment terminals, Transportation Research Part E: Logistics and Transportation Review 49 (1) (2013) 201–216.

[53] J. Muñuzuri, A. Lorenzo-Espejo, A. Pegado-Bardayo, A. Escudero-Santana, Integrated scheduling of vessels, cranes and trains to minimize delays in a seaport container terminal, Journal of Marine Science and Engineering 10 (10) (2022) 1506.

[54] G. Chen, K. Govindan, Z. Yang, Managing truck arrivals with time windows to alleviate gate congestion at container terminals, International Journal of Production Economics 141 (1) (2013) 179–188.

[55] M. D. Gracia, R. G. González-Ramírez, J. Mar-Ortiz, The impact of lanes segmentation and booking levels on a container terminal gate congestion, Flexible Services and Manufacturing Journal 29 (2017) 403–432.

[56] M.-H. Phan, K. H. Kim, Collaborative truck scheduling and appointments for trucking companies and container terminals, Transportation Research Part B: Methodological 86 (2016) 37–50.

[57] W. Zhao, A. V. Goodchild, Using the truck appointment system to improve yard efficiency in container terminals, Maritime Economics & Logistics 15 (2013) 101–119.

[58] A. Ramírez-Nafarrate, R. G. González-Ramírez, N. R. Smith, R. Guerra-Olivares, S. Voß, Impact on yard efficiency of a truck appointment system for a port terminal, Annals of Operations Research 258 (2017) 195–216.

[59] E. Zehendner, D. Feillet, Benefits of a truck appointment system on the service quality of inland transport modes at a multimodal container terminal, European Journal of Operational Research 235 (2) (2014) 461–469.

[60] S. Nikghadam, Cooperation between vessel service providers for port call performance improvement (2023).

[61] L. Heilig, S. Voß, Inter-terminal transportation: an annotated bibliography and research agenda, Flexible Services and Manufacturing Journal 29 (1) (2017) 35–63.

[62] J.-F. Ding, G.-S. Liang, Using fuzzy mcdm to select partners of strategic alliances for liner shipping, Information sciences 173 (1-3) (2005) 197–225.

[63] M. Z. Solesvik, P. Westhead, Partner selection for strategic alliances: case study insights from the maritime industry, Industrial Management & Data Systems 110 (6) (2010) 841–860.

[64] W. Chen, Z. Yang, W. Pan, Port strategic alliance partner selection using grey target model based on error propagation and vertical projection distance, Journal of Coastal Research (73) (2015) 797–804.

[65] D.-Y. Lin, C.-C. Huang, M. Ng, The coopetition game in international liner shipping, Maritime Policy & Management 44 (4) (2017) 474–495.

[66] Z. Song, W. Tang, R. Zhao, Liner alliances with heterogeneous price level and service competition: Partial vs. full, Omega 103 (2021) 102414.

[67] A. Budipriyanto, B. Wirjodirdjo, N. Pujawan, S. Gurning, Berth allocation problem under uncertainty: A conceptual model using collaborative approach, Procedia Manufacturing 4 (2015) 429–437.

[68] C. A. Kavirathna, T. Kawasaki, S. Hanaoka, Intra-port coopetition under different combinations of terminal ownership, Transportation Research Part E: Logistics and Transportation Review 128 (2019) 132–148.

[69] N. Saeed, O. I. Larsen, An application of cooperative game among container terminals of one port, European Journal of Operational Research 203 (2) (2010) 393–403.

[70] W. Y. Yap, J. S. Lam, An interpretation of inter-container port relationships from the demand perspective, Maritime Policy & Management 31 (4) (2004) 337–355.

[71] J.-b. Li, Y.-s. Oh, A research on competition and cooperation between shanghai port and ningbo-zhoushan port, The Asian Journal of Shipping and Logistics 26 (1) (2010) 67–91.

[72] X. Qiu, E. Y. Wong, J. S. L. Lam, Evaluating economic and environmental value of liner vessel sharing along the maritime silk road, Maritime Policy & Management 45 (3) (2018) 336–350.

[73] E. Irannezhad, C. G. Prato, M. Hickman, The effect of cooperation among shipping lines on transport costs and pollutant emissions, Transportation Research Part D: Transport and Environment 65 (2018) 312–323.

[74] K. Pujats, D. Konur, M. Golias, Models for intra-port container terminal cooperation based on volume and vessel transfer, Maritime Policy & Management (2021) 1–24.

[75] C. W. Wong, H. H. Ma, L. C. Leung, Collaboration at the hong kong port–benefits from facility sharing, Policy Research Institute of Global Supply Chain. Hong Kong: Hang Seng Management College (2018).

[76] G. Kim, E. Lee, B. Kim, Strategic port management by consolidating container terminals, The Asian Journal of Shipping and Logistics 38 (1) (2022) 19–24.

[77] P. Rau, S. Spinler, Investment into container shipping capacity: A real options approach in oligopolistic competition, Transportation Research Part E: Logistics and Transportation Review 93 (2016) 130–147.

[78] P. Rau, S. Spinler, Alliance formation in a cooperative container shipping game: Performance of a real options investment approach, Transportation Research Part E: Logistics and Transportation Review 101 (2017) 155–175.

[79] N. Liu, Z. Gong, X. Xiao, Disaster prevention and strategic investment for multiple ports in a region: cooperation or not, Maritime Policy & Management 45 (5) (2018) 585–603.

[80] A. Asadabadi, E. Miller-Hooks, Co-opetition in enhancing global port network resiliency: A multi-leader, common-follower game theoretic approach, Transportation Research Part B: Methodological 108 (2018) 281–298.

[81] W. Li, A. Asadabadi, E. Miller-Hooks, Enhancing resilience through port coalitions in maritime freight networks, Transportation Research Part A: Policy and Practice 157 (2022) 1–23.

[82] D.-W. Song, Port co-opetition in concept and practice, Maritime Policy & Management 30 (1) (2003) 29–44.

[83] J. Chen, X. Liu, X. Zhang, J. He, L. Luo, Optimal bilateral cooperative slot allocation for two liner carriers under a co-chartering agreement, The Journal of Navigation 70 (5) (2017) 1170–1182.

[84] J. Chen, Q. Xu, H. Zhang, Z. Wan, M. Yu, Bilateral slot exchange and co-allocation for liner alliance carriers of containerized maritime logistics, Advanced Engineering Informatics 51 (2022) 101479.

[85] E. Y. C. Wong, K. K. T. Ling, A. H. Tai, J. S. L. Lam, X. Zhang, Three-echelon slot allocation for yield and utilisation management in ship liner operations, Computers & Operations Research 148 (2022) 105983.

[86] D. Ambrosino, A. Sciomachen, A shipping line stowage-planning procedure in the presence of hazardous containers, Maritime Economics & Logistics 23 (2021) 49–70.

[87] D. Wetzel, K. Tierney, Integrating fleet deployment into liner shipping vessel repositioning, Transportation Research Part E: Logistics and Transportation Review 143 (2020) 102101.

[88] E. Y.-C. Wong, K. K.-T. Ling, X. Zhang, Yield and port performance shipping allocation model for revamp service deployments under a dynamic trading landscape, Transportation Research Part C: Emerging Technologies 130 (2021) 103279.

[89] L. Lei, C. Fan, M. Boile, S. Theofanis, Collaborative vs. non-collaborative container-vessel scheduling, Transportation Research Part E: Logistics and Transportation Review 44 (3) (2008) 504–520.

[90] L. B. Reinhardt, D. Pisinger, M. M. Sigurd, J. Ahmt, Speed optimizations for liner networks with business constraints, European Journal of Operational Research 285 (3) (2020) 1127–1140.

[91] H. Meersman, E. Moschouli, L. NanwayBoukani, C. Sys, E. van Hassel, T. Vanelslander, E. Van de Voorde, Evaluating the performance of the vessel train concept, European Transport Research Review 12 (2020) 1–11.

[92] L. Chen, H. Hopman, R. R. Negenborn, Distributed model predictive control for vessel train formations of cooperative multi-vessel systems, Transportation Research Part C: Emerging Technologies 92 (2018) 101–118.

[93] X. Yang, W. Gu, W. Wang, S. Wang, Optimal scheduling of autonomous vessel trains in a hub-and-spoke network, Ocean & Coastal Management 231 (2023) 106386.

[94] B. Martin-Iradi, D. Pacino, S. Ropke, The multiport berth allocation problem with speed optimization: exact methods and a cooperative game analysis, Transportation Science 56 (4) (2022) 972–999.

[95] B. Martin-Iradi, D. Pacino, S. Ropke, An adaptive large neighborhood search heuristic for the multi-port continuous berth allocation problem, European Journal of Operational Research 316 (1) (2024) 152–167.

[96] A. Imai, E. Nishimura, S. Papadimitriou, Berthing ships at a multi-user container terminal with a limited quay capacity, Transportation Research Part E: Logistics and Transportation Review 44 (1) (2008) 136–151.

[97] S. W. Cho, H. J. Park, C. Lee, An integrated method for berth allocation and quay crane assignment to allow for reassignment of vessels to other terminals, Maritime Economics & Logistics 23 (1) (2021) 123–153.

[98] E. Lalla-Ruiz, C. E. Izquierdo, B. M. Batista, J. M. MorenoVega, Decentralized cooperative metaheuristic for the dynamic berth allocation problem, Inteligencia Artificial 18 (55) (2015) 1–11.

[99] H.-L. Ma, C. W.-H. Wong, L. C. Leung, S.-H. Chung, Facility sharing in business-to-business model: A real case study for container terminal operators in hong kong port, International Journal of Production Economics 221 (2020) 107483.

[100] J. He, W. Zhang, Y. Huang, W. Yan, A simulation optimization method for internal trucks sharing assignment among multiple container terminals, Advanced Engineering Informatics 27 (4) (2013) 598–614.

[101] X. Yang, N. Zhao, S. Yu, Combined internal trucks allocation of multiple container terminals with hungarian algorithm, Journal of Coastal Research 103 (SI) (2020) 923–927.

[102] R. Zhang, W. Y. Yun, H. Kopfer, Heuristic-based truck scheduling for inland container transportation, OR spectrum 32 (3) (2010).

[103] K. Braekers, A. Caris, G. K. Janssens, Integrated planning of loaded and empty container movements, OR spectrum 35 (2013) 457–478.

[104] S. Sterzik, H. Kopfer, W.-Y. Yun, Reducing hinterland transportation costs through container sharing, Flexible Services and Manufacturing Journal 27 (2015) 382–402.

[105] S. Fazi, S. K. Choudhary, J.-X. Dong, The multi-trip container drayage problem with synchronization for efficient empty containers re-usage, European Journal of Operational Research (2023).

[106] M. Lai, T. G. Crainic, M. Di Francesco, P. Zuddas, An heuristic search for the routing of heterogeneous trucks with single and double container loads, Transportation Research Part E: Logistics and Transportation Review 56 (2013) 108–118.

[107] Z. Xue, C. Zhang, W.-H. Lin, L. Miao, P. Yang, A tabu search heuristic for the local container drayage problem under a new operation mode, Transportation Research Part E: Logistics and Transportation Review 62 (2014) 136–150.

[108] Z. Xue, W.-H. Lin, L. Miao, C. Zhang, Local container drayage problem with tractor and trailer operating in separable mode, Flexible Services and Manufacturing Journal 27 (2015) 431–450.

[109] S. Shiri, N. Huynh, Assessment of us chassis supply models on drayage productivity and air emissions, Transportation Research Part D: Transport and Environment 61 (2018) 174–203.

[110] F. Schulte, E. Lalla-Ruiz, R. G. González-Ramírez, S. Voß, Reducing port-related empty truck emissions: a mathematical approach for truck appointments with collaboration, Transportation Research Part E: Logistics and Transportation Review 105 (2017) 195–212.

[111] J. You, L. Miao, C. Zhang, Z. Xue, A generic model for the local container drayage problem using the emerging truck platooning operation mode, Transportation Research Part B: Methodological 133 (2020) 181–209.

[112] X. Yan, M. Xu, C. Xie, Local container drayage problem with improved truck platooning operations, Transportation Research Part E: Logistics and Transportation Review 169 (2023) 102992.

[113] S. Chen, H. Wang, Q. Meng, Autonomous truck scheduling for container transshipment between two seaport terminals considering platooning and speed optimization, Transportation Research Part B: Methodological 154 (2021) 289–315.

[114] N. Pourmohammad-Zia, F. Schulte, R. G. González-Ramírez, S. Voß, R. R. Negenborn, A robust optimization approach for platooning of automated ground vehicles in port hinterland corridors, Computers & Industrial Engineering 177 (2023) 109046.

[115] C. A. Kavirathna, T. Kawasaki, S. Hanaoka, Y. M. Bandara, Cooperation with a vessel transfer policy for coopetition among container terminals in a single port, Transport Policy 89 (2020) 1–12.

[116] C. Macharis, Y. M. Bontekoning, Opportunities for or in intermodal freight transport research: A review, European Journal of operational research 153 (2) (2004) 400–416.

[117] A. K. Bhoopalam, N. Agatz, R. Zuidwijk, Planning of truck platoons: A literature review and directions for future research, Transportation research part B: methodological 107 (2018) 212–228.

[118] M. A. Krajewska, H. Kopfer, G. Laporte, S. Ropke, G. Zaccour, Horizontal cooperation among freight carriers: request allocation and profit sharing, Journal of the Operational Research Society 59 (11) (2008) 1483–1491.

[119] C. Vanovermeire, K. Sörensen, Integration of the cost allocation in the optimization of collaborative bundling, Transportation Research Part E: Logistics and Transportation Review 72 (2014) 125–143.

[120] M. Guajardo, M. Rönnqvist, Operations research models for coalition structure in collaborative logistics, European Journal of Operational Research 240 (1) (2015) 147–159.

[121] N. Öner, G. Kuyzu, Core stable coalition selection in collaborative truckload transportation procurement, Transportation Research Part E: Logistics and Transportation Review 154 (2021) 102447.

[122] M. Guajardo, K. Jörnsten, Common mistakes in computing the nucleolus, European Journal of Operational Research 241 (3) (2015) 931–935.

[123] C. Vanovermeire, K. Sörensen, Measuring and rewarding flexibility in collaborative distribution, including two-partner coalitions, European Journal of Operational Research 239 (1) (2014) 157–165.

[124] Q. An, H. Chen, Double-type player games and proportional cross-evaluation allocation method for collaborative logistics, Transportation Research Part C: Emerging Technologies 135 (2022) 103517.

[125] A. Giudici, T. Lu, C. Thielen, R. Zuidwijk, An analysis of the stability of hinterland container transport cooperation, Transportation Science 55 (5) (2021) 1170–1186.

[126] Y. Bouchery, B. Hezarkhani, G. Stauffer, Coalition formation and cost sharing for truck platooning, Transportation Research Part B: Methodological 165 (2022) 15–34.

[127] M. Frisk, M. Göthe-Lundgren, K. Jörnsten, M. Rönnqvist, Cost allocation in collaborative forest transportation, European Journal of Operational Research 205 (2) (2010) 448–458.

[128] S. Lozano, P. Moreno, B. Adenso-Díaz, E. Algaba, Cooperative game theory approach to allocating benefits of horizontal cooperation, European Journal of Operational Research 229 (2) (2013) 444–452.

[129] M. Wen, R. Larsen, S. Ropke, H. L. Petersen, O. B. Madsen, Centralised horizontal cooperation and profit sharing in a shipping pool, Journal of the Operational Research Society 70 (5) (2019) 737–750.

[130] T. Notteboom, J. Siu Lee Lam, Dealing with uncertainty and volatility in shipping and ports, Maritime Policy & Management 41 (2014) 611–614.

[131] L. Zhen, D.-F. Chang, A bi-objective model for robust berth allocation scheduling, Computers & Industrial Engineering 63 (1) (2012) 262–273.

[132] M. Golias, I. Portal, D. Konur, E. Kaisar, G. Kolomvos, Robust berth scheduling at marine container terminals via hierarchical optimization, Computers & Operations Research 41 (2014) 412–422.

[133] Q. Zeng, Z. Yang, X. Hu, Disruption recovery model for berth and quay crane scheduling in container terminals, Engineering Optimization 43 (9) (2011) 967–983.

[134] D.-H. Lee, J. G. Jin, J. H. Chen, Terminal and yard allocation problem for a container transshipment hub with multiple terminals, Transportation Research Part E: Logistics and Transportation Review 48 (2) (2012) 516–528.

[135] Y. Xu, Y. Du, Y. Li, H. Zhang, Collaborative emergency berth scheduling based on decentralized decision and price mechanism, Annals of Operations Research 298 (1) (2021) 525–554.

[136] X. Lyu, J. G. Jin, H. Hu, Berth allocation recovery for container transshipment terminals, Maritime Policy & Management 47 (4) (2020) 558–574.

[137] F. Meisel, C. Bierwirth, A framework for integrated berth allocation and crane operations planning in seaport container terminals, Transportation Science 47 (2) (2013) 131–147.

[138] C. Bierwirth, F. Meisel, A follow-up survey of berth allocation and quay crane scheduling problems in container terminals, European Journal of Operational Research 244 (3) (2015) 675–689.

[139] S. Pratap, A. Nayak, A. Kumar, N. Cheikhrouhou, M. K. Tiwari, An integrated decision support system for berth and ship unloader allocation in bulk material handling port, Computers & industrial engineering 106 (2017) 386–399.

[140] S. Pratap, M. Kumar B, D. Saxena, M. K. Tiwari, Integrated scheduling of rake and stockyard management with ship berthing: a block based evolutionary algorithm, International Journal of Production Research 54 (14) (2016) 4182–4204.

[141] Y.-M. Park, K. H. Kim, A scheduling method for berth and quay cranes, Container terminals and automated transport systems (2005) 159–181.

[142] F. Meisel, C. Bierwirth, Heuristics for the integration of crane productivity in the berth allocation problem, Transportation Research Part E: Logistics and Transportation Review 45 (1) (2009) 196–209.

[143] C. Zhang, L. Zheng, Z. Zhang, L. Shi, A. J. Armstrong, The allocation of berths and quay cranes by using a sub-gradient optimization technique, Computers & Industrial Engineering 58 (1) (2010) 40–50.

[144] C. Yang, X. Wang, Z. Li, An optimization approach for coupling problem of berth allocation and quay crane assignment in container terminal, Computers & Industrial Engineering 63 (1) (2012) 243–253.

[145] E. Lalla-Ruiz, B. Melián-Batista, J. M. Moreno-Vega, A cooperative search for berth scheduling, The Knowledge Engineering Review 31 (5) (2016) 498–507.

[146] G. Giallombardo, L. Moccia, M. Salani, I. Vacca, Modeling and solving the tactical berth allocation problem, Transportation Research Part B: Methodological 44 (2) (2010) 232–245.

[147] T. Wang, X. Wang, Q. Meng, Joint berth allocation and quay crane assignment under different carbon taxation policies, Transportation Research Part B: Methodological 117 (2018) 18–36.

[148] Ç. Iris, D. Pacino, S. Ropke, Improved formulations and an adaptive large neighborhood search heuristic for the integrated berth allocation and quay crane assignment problem, Transportation Research Part E: Logistics and Transportation Review 105 (2017) 123–147.

[149] I. Vacca, M. Salani, M. Bierlaire, An exact algorithm for the integrated planning of berth allocation and quay crane assignment, Transportation Science 47 (2) (2013) 148–161.

[150] D. Prajapati, Y. Daultani, N. Cheikhrouhou, S. Pratap, Identification and ranking of key factors impacting efficiency of indian shipping logistics sector, Opsearch 57 (2020) 765–786.

[151] Y. Xu, Q. Chen, X. Quan, Robust berth scheduling with uncertain vessel delay and handling time, Annals of Operations Research 192 (1) (2012) 123–140.

[152] M. Rodriguez-Molins, L. Ingolotti, F. Barber, M. A. Salido, M. R. Sierra, J. Puente, A genetic algorithm for robust berth allocation and quay crane assignment, Progress in Artificial Intelligence 2 (4) (2014) 177–192.

[153] L. Zhen, L. H. Lee, E. P. Chew, A decision model for berth allocation under uncertainty, European Journal of Operational Research 212 (1) (2011) 54–68.

[154] Ç. Iris, J. S. L. Lam, Recoverable robustness in weekly berth and quay crane planning, Transportation Research Part B: Methodological 122 (2019) 365–389.

[155] X. T. Shang, J. X. Cao, J. Ren, A robust optimization approach to the integrated berth allocation and quay crane assignment problem, Transportation Research Part E: Logistics and Transportation Review 94 (2016) 44–65.

[156] M. Z. Li, J. G. Jin, C. X. Lu, Real-time disruption recovery for integrated berth allocation and crane assignment in container terminals, Transportation Research Record 2479 (2015) 49–59.

[157] N. Umang, M. Bierlaire, A. L. Erera, Real-time management of berth allocation with stochastic arrival and handling times, Journal of Scheduling 20 (2017) 67–83.

[158] X. Xiang, C. Liu, L. Miao, Reactive strategy for discrete berth allocation and quay crane assignment problems under uncertainty, Computers & Industrial Engineering 126 (2018) 196–216.

[159] L. Zhen, E. P. Chew, L. H. Lee, An integrated model for berth template and yard template planning in transshipment hubs, Transportation Science 45 (4) (2011) 483–504.

[160] E. Ursavas, S. X. Zhu, Optimal policies for the berth allocation problem under stochastic nature, European Journal of Operational Research 255 (2) (2016) 380–387.

[161] X. Schepler, S. Balev, S. Michel, É. Sanlaville, Global planning in a multi-terminal and multi-modal maritime container port, Transportation Research Part E: Logistics and Transportation Review 100 (2017) 38–62.

[162] A. Sheikholeslami, R. Ilati, A sample average approximation approach to the berth allocation problem with uncertain tides, Engineering Optimization 50 (10) (2018) 1772–1788.

[163] J. Liu, J. Wang, Carrier alliance incentive analysis and coordination in a maritime transport chain based on service competition, Transportation Research Part E: Logistics and Transportation Review 128 (2019) 333–355.

[164] A. Cook, L. Delgado, G. Tanner, S. Cristóbal, Measuring the cost of resilience, Journal of Air Transport Management 56 (2016) 38–47.

[165] S. N. Sirimanne, J. Hoffman, W. Juan, R. Asariotis, M. Assaf, G. Ayala, H. Benamara, D. Chantrel, J. Hoffmann, A. Premti, et al., Review of maritime transport 2021, in: United Nations Conference on Trade and Development, Geneva, Switzerland, 2019.

[166] D. Steenken, S. Voß, R. Stahlbock, Container terminal operation and operations research-a classification and literature review, OR spectrum 26 (1) (2004) 3–49.

[167] R. Stahlbock, S. Voß, Operations research at container terminals: a literature update, OR spectrum 30 (1) (2008) 1–52.

[168] N. Umang, From container terminals to bulk ports: models and algorithms for integrated planning and robust scheduling, Ph.D. thesis, Ph. D. Thesis. École Polytechnique Fédérale de Lausanne (2014).

[169] V. H. Barros, T. S. Costa, A. C. Oliveira, L. A. Lorena, Model and heuristic for berth allocation in tidal bulk ports with stock level constraints, Computers & Industrial Engineering 60 (4) (2011) 606–613.

[170] I. Krimi, R. Todosijević, R. Benmansour, M. Ratli, A. A. El Cadi, A. Aloullal, Modelling and solving the multi-quays berth allocation and crane assignment problem with availability constraints, Journal of Global Optimization 78 (2) (2020) 349–373.

[171] G. M. Ribeiro, G. R. Mauri, S. de Castro Beluco, L. A. N. Lorena, G. Laporte, Berth allocation in an ore terminal with demurrage, despatch and maintenance, Computers & Industrial Engineering 96 (2016) 8–15.

[172] N. Umang, M. Bierlaire, I. Vacca, Exact and heuristic methods to solve the berth allocation problem in bulk ports, Transportation Research Part E: Logistics and Transportation Review 54 (2013) 14–31.

[173] A. T. Ernst, C. Oğuz, G. Singh, G. Taherkhani, Mathematical models for the berth allocation problem in dry bulk terminals, Journal of Scheduling 20 (5) (2017) 459–473.

[174] N. Cheimanoff, F. Fontane, M. N. Kitri, N. Tchernev, A reduced vns based approach for the dynamic continuous berth allocation problem in bulk terminals with tidal constraints, Expert Systems with Applications 168 (2021) 114215.

[175] X. Hu, W. Yan, J. He, Z. Bian, Study on bulk terminal berth allocation based on heuristic algorithm, in: Proceedings of the 2012 International Conference of Modern Computer Science and Applications, Springer, 2013, pp. 413–419.

[176] D. Perez, J. G. Jin, Integrated dedicated berth allocation and specialised handling equipment assignment in bulk ports, International Journal of Shipping and Transport Logistics 12 (6) (2020) 543–562.

[177] H. Bouzekri, G. Alpan, V. Giard, A dynamic hybrid berth allocation problem with routing constraints in bulk ports, in: IFIP International Conference on Advances in Production Management Systems, Springer, 2020, pp. 250–258.

[178] T. Robenek, N. Umang, M. Bierlaire, S. Ropke, A branch-and-price algorithm to solve the integrated berth allocation and yard assignment problem in bulk ports, European Journal of Operational Research 235 (2) (2014) 399–411.

[179] A. D. de León, E. Lalla-Ruiz, B. Melián-Batista, J. M. Moreno-Vega, A machine learning-based system for berth scheduling at bulk terminals, Expert Systems with Applications 87 (2017) 170–182.

[180] A. D. de León, E. Lalla-Ruiz, B. Melián-Batista, J. M. Moreno-Vega, A simulation–optimization framework for enhancing robustness in bulk berth scheduling, Engineering applications of artificial intelligence 103 (2021) 104276.

[181] O. Unsal, C. Oguz, An exact algorithm for integrated planning of operations in dry bulk terminals, Transportation Research Part E: Logistics and Transportation Review 126 (2019) 103–121.

[182] J. Peng, Z. Zhou, R. Li, A collaborative berth allocation problem with multiple ports based on genetic algorithm, Journal of Coastal Research (73 (10073)) (2015) 290–297.

[183] N. Cheimanoff, F. Fontane, M. N. Kitri, N. Tchernev, Exact and heuristic methods for the berth allocation problem with multiple continuous quays in tidal bulk terminals, Expert Systems with Applications 201 (2022) 117141.

[184] R. Lassoued, A. Elloumi, The discrete and dynamic berth allocation problem in bulk port, in: 2019 6th International Conference on Control, Decision and Information Technologies (CoDIT), IEEE, 2019, pp. 1976–1980.

[185] J. L. M. d. Andrade, G. C. Menezes, An integrated planning, scheduling, yard allocation and berth allocation problem in bulk ports: Model and heuristics, in: International Conference on Computational Logistics, Springer, 2021, pp. 3–20.

[186] Hapag-Lloyd, Gemini cooperation hapag-lloyd & maersk are entering into an operational cooperation in 2025 (2024).
URL https://www.hapag-lloyd.com/content/dam/website/downloads/pdf/Gemini_Cooperation_Hapag-Lloyd_Customer_Value_Proposition.pdf

[187] F. Schulte, E. Lalla-Ruiz, S. Schwarze, R. G. González-Ramırez, S. Voß, Scalable core and shapley value allocation methods for collaborative transportation, Tech. rep., University of Hamburg (2019).

[188] M. M. Golias, M. Boile, S. Theofanis, Berth scheduling by customer service differentiation: A multi-objective approach, Transportation Research Part E: Logistics and Transportation Review 45 (6) (2009) 878–892.

[189] L. Schrooten, I. De Vlieger, L. I. Panis, K. Styns, R. Torfs, Inventory and forecasting of maritime emissions in the belgian sea territory, an activity-based emission model, Atmospheric Environment 42 (4) (2008) 667–676.

[190] Y. Du, Q. Chen, X. Quan, L. Long, R. Y. Fung, Berth allocation considering fuel consumption and vessel emissions, Transportation Research Part E: Logistics and Transportation Review 47 (6) (2011) 1021–1037.

[191] N. Lang, A. Veenstra, A quantitative analysis of container vessel arrival planning strategies, OR spectrum 32 (3) (2010) 477–499.

[192] J. F. Alvarez, T. Longva, E. S. Engebrethsen, A methodology to assess vessel berthing and speed optimization policies, Maritime economics & logistics 12 (4) (2010) 327–346.

[193] J. Yu, G. Tang, X. Song, Collaboration of vessel speed optimization with berth allocation and quay crane assignment considering vessel service differentiation, Transportation Research Part E: Logistics and Transportation Review 160 (2022) 102651.

[194] O. Ö. Özener, Ö. Ergun, Allocating costs in a collaborative transportation procurement network, Transportation Science 42 (2) (2008) 146–165.

[195] N. R. Sabar, S. Y. Chong, G. Kendall, A hybrid differential evolution algorithm–game theory for the berth allocation problem, in: Proceedings of the 18th Asia Pacific Symposium on Intelligent and Evolutionary Systems-Volume 2, Springer, 2015, pp. 77–87.

[196] L. Guo, J. Zheng, J. Liang, S. Wang, Column generation for the multi-port berth allocation problem with port cooperation stability, Transportation Research Part B: Methodological 171 (2023) 3–28.

[197] M. Hendriks, D. Armbruster, M. Laumanns, E. Lefeber, J. Udding, Strategic allocation of cyclically calling vessels for multi-terminal container operators, Flexible Services and Manufacturing Journal 24 (3) (2012) 248–273.

[198] M. A. Dulebenets, M. M. Golias, S. Mishra, A collaborative agreement for berth allocation under excessive demand, Engineering Applications of Artificial Intelligence 69 (2018) 76–92.

[199] J. Drechsel, A. Kimms, Computing core allocations in cooperative games with an application to cooperative procurement, International Journal of Production Economics 128 (1) (2010) 310–321.

[200] H. Xiao, Q. Fang, Arboricity games: the core and the nucleolus, Mathematical Programming 198 (1) (2023) 1–25.

[201] D. Schmeidler, The nucleolus of a characteristic function game, SIAM Journal on applied mathematics 17 (6) (1969) 1163–1170.

[202] F. Perea, J. Puerto, A heuristic procedure for computing the nucleolus, Computers & Operations Research 112 (2019) 104764.

[203] T.-D. Nguyen, L. Thomas, Finding the nucleoli of large cooperative games, European Journal of Operational Research 248 (3) (2016) 1078–1092.

[204] M. Benedek, J. Fliege, T.-D. Nguyen, Finding and verifying the nucleolus of cooperative games, Mathematical Programming 190 (1) (2021) 135–170.

[205] Z.-Y. Song, P. Chhetri, G. Ye, P. T.-W. Lee, Green maritime logistics coalition by green shipping corridors: a new paradigm for the decarbonisation of the maritime industry, International Journal of Logistics Research and Applications (2023) 1–17.

[206] Y.-S. Chen, In response to global climate change goals, exploring the development strategy for decarbonizing the shipping industry in taiwan, Ocean & Coastal Management 252 (2024) 107108.

[207] G. M. Forum, Annual progress report on green shipping corridors-2023 (2023). URL https://cms.globalmaritimeforum.org/wp-content/uploads/2023/11/Global-Maritime-Forum_Annual-Progress-Report-on-Green-Shipping-Corridors_2023.pdf

[208] J. Huang, X. Duan, A comprehensive review of emission reduction technologies for marine transportation, Journal of Renewable and Sustainable Energy 15 (3) (2023).

[209] Y. Zhao, Y. Chen, K. Fagerholt, E. Lindstad, J. Zhou, Pathways towards carbon reduction through technology transition in liner shipping, Maritime Policy & Management (2023) 1–23.

[210] M. Ben Ahmed, E. Molland, T. Tomasgard, Challenges and opportunities for adopting green technologies in maritime transportation planning, in: IFIP International Conference on Advances in Production Management Systems, Springer, 2023, pp. 620–633.

[211] E. A. Bouman, E. Lindstad, A. I. Rialland, A. H. Strømman, State-of-the-art technologies, measures, and potential for reducing ghg emissions from shipping–a review, Transportation Research Part D: Transport and Environment 52 (2017) 408–421.

[212] T. G. Péra, D. B. Bartholomeu, C. T. Su, J. V. C. Filho, Transporting soybean from brazil to china through green corridors, in: Operations Management for Social Good: 2018 POMS International Conference in Rio, Springer, 2020, pp. 635–646.

[213] D. A. d. Moura, R. C. Botter, J. Netto, Challenges for implementation of the green corridor in brazil, in: Maritime Transportation and Harvesting of Sea Resources. International Congress of the International Maritime Association of the Mediterranean, Lisbon, Portugal, 2017.

[214] A. Hessevik, Green shipping networks as drivers of decarbonization in offshore shipping companies, Maritime Transport Research 3 (2022) 100053.

[215] O. Schinas, M. Butler, Feasibility and commercial considerations of lng-fueled ships, Ocean Engineering 122 (2016) 84–96.

[216] I. S. Seddiek, N. R. Ammar, Technical and eco-environmental analysis of blue/green ammonia-fueled ro/ro ships, Transportation Research Part D: Transport and Environment 114 (2023) 103547.

[217] O. Melnyk, O. Onishchenko, S. Onyshchenko, N. Yaremenko, E. Maliuha, I. Honcharuk, O. Shamov, Innovative technologies for the maritime industry: Hydrogen fuel as a promising direction, in: Modern Technologies in Energy and Transport, Springer, 2023, pp. 23–34.

[218] H. N. Psaraftis, P. Amboy, Psaraftis, Sustainable shipping, Springer, 2019.

[219] K. Chen, Z. Yang, T. Notteboom, The design of coastal shipping services subject to carbon emission reduction targets and state subsidy levels, Transportation Research Part E: Logistics and Transportation Review 61 (2014) 192–211.

[220] Z. Yang, X. Xin, K. Chen, A. Yang, Coastal container multimodal transportation system shipping network design—toll policy joint optimization model, Journal of Cleaner Production 279 (2021) 123340.

[221] H. N. Psaraftis, T. Zis, S. Lagouvardou, A comparative evaluation of market based measures for shipping decarbonization, Maritime Transport Research 2 (2021) 100019.

[222] P. Cariou, E. Lindstad, H. Jia, The impact of an eu maritime emissions trading system on oil trades, Transportation Research Part D: Transport and Environment 99 (2021) 102992.

[223] M. Kuby, S. Lim, The flow-refueling location problem for alternative-fuel vehicles, Socio-Economic Planning Sciences 39 (2) (2005) 125–145.

[224] A. R. Nerheim, Maritime lng fuel systems for small vessels—a survey of patents, Transportation Research Part D: Transport and Environment 119 (2023) 103766.

[225] M. Kuby, I. Capar, J.-G. Kim, Efficient and equitable transnational infrastructure planning for natural gas trucking in the european union, European Journal of Operational Research 257 (3) (2017) 979–991.

[226] M. Doymus, G. D. Sakar, S. T. Yildiz, A. Acik, Small-scale lng supply chain optimization for lng bunkering in turkey, Computers & Chemical Engineering 162 (2022) 107789.

[227] R. Agarwal, Ö. Ergun, Ship scheduling and network design for cargo routing in liner shipping, Transportation Science 42 (2) (2008) 175–196.

[228] M. M.-K. M. C. for Zero Carbon Shipping, Northern european & baltic green corridor prefeasibility study (2022).
URL https://www.zerocarbonshipping.com/publications/northern-european-baltic-green-corridor-prefeasibility-study/

[229] T. Butler, J. Kopp, M. Moritz, M. Stoelingo, K. v. Dijk, J. Pruyn, Gaps and developments ammonia supply chain for future demand (2021).
URL https://www.magpie-ports.eu/wp-content/uploads/2023/05/Deliverable-D3.6-Ammonia-Supply-Chain.pdf

[230] The next wave: Green corridors (2021).
URL https://www.globalmaritimeforum.org/publications/the-next-wave-green-corridors

[231] J. J. Corbett, H. Wang, J. J. Winebrake, The effectiveness and costs of speed reductions on emissions from international shipping, Transportation Research Part D: Transport and Environment 14 (8) (2009) 593–598.

[232] Z. Chu, R. Yan, S. Wang, Evaluation and prediction of punctuality of vessel arrival at port: a case study of hong kong, Maritime Policy & Management (2023) 1–29.

Glossary

List of abbreviations

Below follows a list of abbreviations in this thesis.

GHG	Greenhouse Gas
IMO	International Maritime Organization
PCS	Port Community System
IoT	Internet of Things
AI	Artificial Intelligence
OR	Operation Research
ITT	Inter-terminal Transport
TAS	Truck Appointment System
JIT	Just In Time
BVS	Blue Visby Solution
BAP	Berth Allocation Problem
ILP	Integer Linear Programming
FSLP	Flexible Ship Loading Problem
TQC	Tandem Quay Crane
AGV	Automated Guided Vehicle
QC	Quay Crane
YC	Yard Crane
IP	Integer Programming
MIP	Mixed Integer Programming
LSFRDP	Liner Shipping Fleet Deployment and Repositioning Problem
FRP	Fleet Repositioning Problem
ALNS	Adaptive Large Neighborhood Search
BACAP	Berth Allocation and Quay Crane Assignment
m-TSPTW	Multiple Traveling Salesman Problem with Time Window
TEU	Twenty-foot Equivalent Unit
SWO	Squeaky Wheel Optimization
TS	Tabu Search
BACSP	Berth Allocation and Quay Crane Scheduling Problem
BP	Branch and Price
HCBAP	Horizontal Collaborative Berth Allocation Problem
VCBAP	Vertical Collaborative Berth Allocation Problem

RG	Row Generation
PSC	Proportional to Stand-alone Costs
EU ETS	European Emission Trading System
LSNDP	Liner Shipping Network Design Problem
FRLM	Flow Refueling Location Models

Samenvatting

Zeescheepvaart is essentieel voor de wereldhandel en vereist de gecoördineerde inspanningen van rederijen, havens en logistieke dienstverleners. Het verbeteren van de samenwerking tussen deze belanghebbenden is van cruciaal belang voor het verbeteren van de operationele efficiëntie, vooral bij het aangaan van de uitdagingen die COVID-19 met zich meebrengt en het doel om tegen 2050 een netto-nul-uitstoot te bereiken. Technologische ontwikkelingen zoals het Internet of Things (IoT), 5G-netwerken, big data en Blockchain hebben nieuwe mogelijkheden gecreëerd voor samenwerking en de ontwikkeling van innovatieve zakelijke raamwerken in de transportsector. De eerste gezamenlijke inspanningen waren gericht op het vergroten van het concurrentievermogen, maar de nadruk is verschoven naar het bereiken van ecologische duurzaamheid en veerkracht.

De afgelopen decennia heeft onderzoek de aanzienlijke voordelen van samenwerking in maritieme scheepvaartketens benadrukt. Studies ter ondersteuning van operationele praktijken moeten echter nog steeds worden uitgebreid, verspreid en gefragmenteerd. Het implementeren van samenwerkingsstrategieën is een uitdaging, omdat deze nieuwe benaderingen extra inspanningen in planningsmodellen voor samenwecting vereisen om een effectieve uitvoering te garanderen. Gezien de recente vooruitgang op het gebied van de samenwerking op het gebied van het wegvervoer, is het tijd om te onderzoeken hoe academisch onderzoek in de maritieme sector zich ontwikkelt. Dit proefschrift classificeert dimensies en werpt licht op Operations Research (OR)-methoden voor collaboratieve maritieme en havenoperaties. Het onderzoekt hoe samenwerking op het gebied van maritiem transport zich verhoudt tot en verschilt van andere domeinen van collaboratief transport. Bij het implementeren van samenwerkingsmodellen is het essentieel om rekening te houden met de uiteenlopende belangen van meerdere belanghebbenden en duidelijke prikkels te ontwerpen om deelname aan ad-hoc-samenwerkingen te motiveren. De onderzoeksvraag die in dit proefschrift wordt behandeld is: *Hoe kunnen samenwerkingsstrategieën bijdragen aan maritieme en havenactiviteiten in de richting van hogere efficiëntie, veerkracht en het koolstofvrij maken?*

Ten eerste biedt het delen van middelen nieuwe mogelijkheden voor optimalisatie van de besluitvorming en introduceert het tegelijkertijd nieuwe OK-uitdagingen. Voor terminals beperkt de capaciteit van ligplaatsen en kadekranen de efficiëntie van de havenactiviteiten, wat vraagt om innovatieve samenwerkingsvormen en bijbehorende planningsmodellen. Om de veerkracht van de zeescheepvaart te vergroten zijn modellen nodig met praktische afwegingen voor verstoringen. Dit proefschrift onderzoekt een innovatieve benadering van ligplaatsplanning gebaseerd op horizontale samenwerking en stelt een geïntegreerd ligplaatsmodel voor als aanvulling op verticale samenwerkingsvormen.

Ten tweede is het vanuit praktisch oogpunt van cruciaal belang om effectieve stimuleringsregelingen voor het vormen van samenwerking te identificeren. In horizontale samenwerkingsverbanden, waar de leden vaak concurrerend zijn, zijn samenwerkingsprikkels essentieel voor beslissingsondersteunende modellen bij gezamenlijke planning. Dit proefschrift onderzoekt een nieuwe vorm van horizontale samenwerking bij de toewijzing van ligplaatsen, gebaseerd op terminale samenwerking, en stelt exacte en stabiele samenwerkingsmechanismen voor die gebruik maken van de kern en de nucleolus. Er zijn twee exacte op rijgeneratie gebaseerde algoritmen ontwikkeld om realistische instantiegroottes op te lossen, waardoor algemene oplossingsbenaderingen worden geboden voor een groot aantal gerelateerde (np-harde) problemen op het gebied van samenwerkingstoewijzing, routering of planning.

Ten derde richten bestaande onderzoeken zich primair op het optimaliseren van het langzaam stomen van schepen en havenafhandelingsactiviteiten om de brandstofkosten te verlagen en zo bij te dragen aan het koolstofvrij maken. De impact van deze aanpak op de emissiereductie is echter beperkt. Het ambitieuze doel om een koolstofneutraal 2050 te bereiken vereist dat regeringen, onderzoekers en maritieme praktijkmensen gezamenlijk prioriteit geven aan het koolstofarm maken van de economie. Dit proefschrift presenteert de eerste optimalisatieaanpak voor het ontwerpen van groene maritieme corridors en biedt kritische richtlijnen voor beleidsmakers en belanghebbenden uit de sector bij het implementeren van maritieme groene corridors op operationeel niveau.

Dit proefschrift biedt een reeks benaderingen voor veerkrachtige en koolstofarme gezamenlijke maritieme en havenoperaties. Het bevestigt het potentieel voor geavanceerde samenwerking om de efficiëntie, veerkracht en het koolstofarm maken van de zeescheepvaart te verbeteren. Het benadrukt het belang van stabiele toewijzingsmethoden om sterke en duurzame samenwerkingsprikkels te bevorderen.

Summary

Maritime shipping is essential for global trade, requiring the coordinated efforts of shipping lines, ports, and logistics providers. Enhancing collaboration among these stakeholders is crucial for improving operational efficiency, especially in facing the challenges brought by COVID-19 and the goal of achieving net-zero emissions by 2050. Technological advancements such as the Internet of Things (IoT), 5G networks, big data, and Blockchain have created new opportunities for collaboration and the development of innovative business frameworks in the transportation sector. Early collaborative efforts focused on enhancing competitiveness, but the emphasis has shifted towards achieving environmental sustainability and resilience.

Over the past decades, research has highlighted the significant benefits of collaboration in maritime shipping chains. However, studies supporting operational practices still need to be expanded, scattered, and fragmented. Implementing collaborative strategies is challenging, as these new approaches require additional efforts in collaborative planning models to ensure effective execution. Given recent advancements in road transportation collaboration, examining how academic research in the maritime sector is evolving is timely. This thesis classifies dimensions and sheds light on Operations Research (OR) methods for collaborative maritime and port operations. It explores how collaboration in maritime transport compares to and differs from other domains of collaborative transportation. When implementing collaborative models, it is essential to consider the diverse interests of multiple stakeholders and design clear incentives to motivate participation in ad-hoc collaborations. The research question addressed in this thesis is: *How can collaborative strategies contribute to maritime and port operations towards higher efficiency, resilience, and decarbonization?*

First, resource-sharing collaboration opens up new decision-making optimization opportunities while introducing novel OR challenges. For terminals, the capacity of berths and quay cranes limits the efficiency of port operations, calling for innovative collaboration forms and corresponding planning models. To enhance the resilience of maritime shipping, models with practical considerations for disruptions are required. This thesis investigates an innovative berth planning approach based on horizontal collaboration and proposes an integrated berthing model to complement vertical collaboration forms.

Second, from a practical standpoint, it is crucial to identify effective incentive schemes for forming collaboration. In horizontal collaborations, where members are often competitive, collaboration incentives are essential for decision-support models in collaborative planning. This thesis explores a new form of horizontal collaboration in berth allocation based on terminal collaboration and proposes exact and stable collaboration mechanisms using the core and the nucleolus. Two exact row-generation-based algorithms are develo-

ped to solve realistic instance sizes, providing general-purpose solution approaches for a large set of related (np-hard) collaborative assignment, routing, or scheduling problems.

Third, existing studies primarily focus on optimizing the slow steaming of vessels and port handling operations to reduce fuel costs, contributing to decarbonization. However, this approach's impact on emissions reduction is limited. The ambitious goal of achieving carbon-neutral 2050 requires governments, researchers, and maritime practitioners to prioritize decarbonization efforts collaboratively. This thesis presents the first optimization approach for designing green maritime corridors, offering critical guidance for policymakers and industry stakeholders on implementing maritime green corridors at the operational level.

This thesis provides a series of approaches for resilient and decarbonized collaborative maritime and port operations. It confirms the potential for advanced collaboration to enhance maritime shipping efficiency, resilience, and decarbonization. It highlights the importance of stable allocation methods to foster strong and lasting collaboration incentives.

Curriculum vitae

Xiaohuan Lyu was born on July 14, 1995 in Yantai, China. She obtained her B.Sc. degree in Logistics Engineering at Dalian Maritime University in 2017. After this, she went to Shanghai Jiao Tong University for her Master study under supervision of Prof. Jiangang Jin and obtained the M.Sc. degree in Transportation Engineering in 2020.

In December 2020, Xiaohuan Lyu started pursuing her PhD degree supervised by Prof. Dr. Rudy R. Negenborn and Dr. Frederik Schulte at the Department of Maritime Technology and Transport, Delft University of Technology, Delft, the Netherlands. In her PhD project, she investigated collaborative strategies to improve efficiency, resilience, and decarbonization for maritime and port transportation. Her research interests include operations research, cooperative game theory, and their application in port logistics and maritime transportation.

Publications

1. X. Lyu, R. R. Negenborn, X. Shi, F. Schulte, A collaborative berth planning approach for disruption recovery. IEEE Open Journal of Intelligent Transportation Systems 3(2022) 153–164.

2. X. Lyu, F. Schulte, Hybrid berth allocation for bulk ports with unavailability and stock level constraints. In Proceedings of 13th International Conference on Computational Logistics, Barcelona, Spain, 2022, pp. 3–15.

3. X. Lyu, E. Lalla-Ruiz, F. Schulte, The collaborative berth allocation problem with row-generation algorithms for stable cost allocations. Under revision (2024)

4. X. Lyu, K. Tierney, F. Schulte, Collaborative maritime and port operations: A literature review and roadmap. Submitted (2024).

5. X. Lyu, R. R. Negenborn, F. Schulte, The network design and refueling station location problem for green maritime corridors and emission trading. To be submitted (2024).

Extended abstracts

1. X. Lyu, E. Lalla-Ruiz and F. Schulte (2023). Collaborative Berth Allocation with Row Generation Methods for the Core and Nucleolus. Abstract at Transportation

Science and Logistics Society Workshop, Chicago.

2. X. Lyu and F. Schulte (2023). The Refueling Station Location Problem with Green Maritime Corridors. Abstract at The 23rd Conference of the International Federation of Operational Research Societies, Santiago, Chile.

3. X. Lyu, R. R. Negenborn, X. Shi, and F. Schulte (2021). A collaborative berth planning model in response to disruptions.In Proceedings of 12th International Conference on Computational Logistics, University of Twente, Enschede, The Netherlands, 2021.

4. X. Lyu and F. Schulte (2021). Collaborative maritime transportation: a literature survey In Proceedings of the International Association of Maritime Economists Conference, Rotterdam, The Netherlands, 2021.

TRAIL Thesis Series

The following list contains the most recent dissertations in the TRAIL Thesis Series. For a complete overview of more than 400 titles see the TRAIL website: www.rsTRAIL.nl.
The TRAIL Thesis Series is a series of the Netherlands TRAIL Research School on transport, infrastructure and logistics.

Lyu, X., *Collaboration for Resilient and Decarbonized Maritime and Port Operations*, T2024/14, November 2024, TRAIL Thesis Series, the Netherlands

Nicolet, A., *Choice-Driven Methods for Decision-Making in Intermodal Transport: Behavioral heterogeneity and supply-demand interactions*, T2024/13, November 2024, TRAIL Thesis Series, the Netherlands

Kougiatsos, N., *Safe and Resilient Control for Marine Power and Propulsion Plants*, T2024/12, November 2024, TRAIL Thesis Series, the Netherlands

Uijtdewilligen, T., *Road Safey of Cyclists in Dutch Cities*, T2024/11, November 2024, TRAIL Thesis Series, the Netherlands

Liu, X., *Distributed and Learning-based Model Predictive Control for Urban Rail Transit Networks*, T2024/10, October 2024, TRAIL Thesis Series, the Netherlands

Clercq, G. K. de, *On the Mobility Effects of Future Transport Modes*, T2024/9, October 2024, TRAIL Thesis Series, the Netherlands

Dreischerf, A.J., *From Caveats to Catalyst: Accelerating urban freight transport sustainability through public initiatives*, T2024/8, September 2024, TRAIL Thesis Series, the Netherlands

Zohoori, B., *Model-based Risk Analysis of Supply Chains for Supporting Resilience*, T2024/7, October 2024, TRAIL Thesis Series, the Netherlands

Poelman, M.C., *Predictive Traffic Signal Control under Uncertainty: Analyzing and Reducing the Impact of Prediction Errors*, T2024/6, October 2024, TRAIL Thesis Series, the Netherlands

Berge, S.H., *Cycling in the age of automation :Enhancing cyclist interaction with automated vehicles through human-machine interfaces*, T2024/5, September 2024, TRAIL Thesis Series, the Netherlands

Wu, K., *Decision-Making and Coordination in Green Supply Chains with Asymmetric In-*

formation, T2024/4, July 2024, TRAIL Thesis Series, the Netherlands

Wijnen, W., *Road Safety and Welfare*, T2024/3, May 2024, TRAIL Thesis Series, the Netherlands

Caiati, V., *Understanding and Modelling Individual Preferences for Mobility as a Service*, T2024/2, March 2024, TRAIL Thesis Series, the Netherlands

Vos, J., *Drivers' Behaviour on Freeway Curve Approach*, T2024/1, February 2024, TRAIL Thesis Series, the Netherlands

Geržinič, N., *The Impact of Public Transport Disruptors on Travel Behaviour*, T2023/20, December 2023, TRAIL Thesis Series, the Netherlands

Dubey, S., *A Flexible Behavioral Framework to Model Mobility on-Demand Service Choice Preference*, T2023/19, November 2023, TRAIL Thesis Series, the Netherlands

Sharma, S., *On-trip Behavior of Truck Drivers on Freeways: New mathematical models and control methods*, T2023/18, October 2023, TRAIL Thesis Series, the Netherlands

Ashkrof, P., *Supply-side Behavioural Dynamics and Operations of Ride-sourcing Platforms*, T2023/17, October 2023, TRAIL Thesis Series, the Netherlands

Sun, D., *Multi-level and Learning-based Model Predictive Control for Traffic Management*, T2023/16, October 2023, TRAIL Thesis Series, the Netherlands

Brederode, L.J.N., *Incorporating Congestion Phenomena into Large Scale Strategic Transport Model Systems*, T2023/15, October 2023, TRAIL Thesis Series, the Netherlands

Hernandez, J.I., *Data-driven Methods to study Individual Choice Behaviour: with applications to discrete choice experiments and Participatory Value Evaluation experiments*, T2023/14, October 2023, TRAIL Thesis Series, the Netherlands

Aoun, J., *Impact Assessment of Train-Centric Rail Signaling Technologies*, T2023/13, October 2023, TRAIL Thesis Series, the Netherlands

Pot, F.J., *The Extra Mile: Perceived accessibility in rural areas*, T2023/12, September 2023, TRAIL Thesis Series, the Netherlands

Nikghadam, S., *Cooperation between Vessel Service Providers for Port Call Performance Improvement*, T2023/11, July 2023, TRAIL Thesis Series, the Netherlands

Li, M., *Towards Closed-loop Maintenance Logistics for Offshore Wind Farms: Approaches for strategic and tactical decision-making*, T2023/10, July 2023, TRAIL Thesis Series, the Netherlands

Berg, T. van den, *Moral Values, Behaviour, and the Self: An empirical and conceptual analysis*, T2023/9, May 2023, TRAIL Thesis Series, the Netherlands

Shelat, S., *Route Choice Behaviour under Uncertainty in Public Transport Networks: Stated and revealed preference analyses*, T2023/8, June 2023, TRAIL Thesis Series, the Netherlands

Zhang, Y., *Flexible, Dynamic, and Collaborative Synchromodal Transport Planning Consi-*

dering Preferences, T2023/7, June 2023, TRAIL Thesis Series, the Netherlands

Kapetanović, M., *Improving Environmental Sustainability of Regional Railway Services*, T2023/6, June 2023, TRAIL Thesis Series, the Netherlands