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Invited Review

Collaborative maritime and port transportation: A literature review

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ABSTRACT

Maritime shipping plays a vital role in global trade, involving a multitude of actors such as shipping lines, ports, and diverse logistics providers. Collaborative operations planning among those actors is imperative to advance overall efficiency and comply with increasingly strict decarbonization policies. Recent events such as the COVID-19 pandemic and the Red Sea crisis have further highlighted this need for collaboration and have led the sector to create new forms of collaboration to enhance its resilience. Although collaborative transportation strategies have been suggested for decades, the related literature on maritime transport remains fragmented, lacking a comprehensive literature review of related research as is available for other transportation modes. In this work, we present a systematic survey on collaboration within the maritime and port transportation sector, taking a critical look at the challenges these collaborative systems face and mapping ways in which Operations Research (OR) methods are used to address them. Building on the two main forms of vertical and horizontal collaborations, we distinguish the involved stakeholders, analyze collaboration approaches, classify decision support and OR approaches, and discuss practical applications, leading to a research agenda that outlines specific challenges for future research. In this way, we connect the fragmented problems and approaches to a roadmap for future collaborative maritime and port transportation systems. This survey helps maritime researchers and practitioners find the right methods for their challenges and gain insight into directions for future collaboration, catalyzing both further research in academia and industrial implementations. This survey further facilitates advanced collaboration in maritime transportation systems, showing pathways towards visions of large-scale collaboration such as the Physical Internet.

1. Introduction

Maritime freight transportation 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. Although there was a 3.8% reduction in international seaborne trade flows in 2020 because of the COVID-19 pandemic, recent reports indicate a 3.2% growth in 2021, with a volume of 11 billion tons (Sirimanne et al., 2019). Due to the current global resource scarcity and climate change crisis, the maritime freight shipping industry faces significant pressure to enhance efficiency, resilience, and decarbonization toward a zero-emission future. Encouraged by the success of existing collaboration forms in the maritime sector and the trend of the sharing economy with successful implementations of collaborative models in road transportation (e.g., Uber Freight), the maritime sector increasingly investigates advanced collaboration among multiple stakeholders to address the above challenges.

The general concept of collaboration can be defined as “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” (Cruijssen et al., 2007). Collaboration among multiple stakeholders in transportation facilitates the sharing and coordinating of resources, including vehicles, facilities, and transport requests, leading to increased efficiency. Maritime and port transportation have a history of collaboration. Early types of collaboration, such as shipping pools, were primarily directed at the competitive position of the participants (Haralambides, 1996), while later environmental and resilience objectives have become further motives. Collaboration in maritime and port transportation has potential for significant improvements of these objectives, but past experiences have shown the challenging nature of this approach, as it requires additional efforts in collaborative planning models. Technological advancement in recent years, particularly the real-time transmission of information, has created new opportunities for conventional forms of collaboration and

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promoted the innovation of collaborative business frameworks in the maritime shipping industry. These developments with new features require supportive planning models.

A significant body of research has highlighted the benefits of collaboration for maritime transportation chains. Tan et al. (2018) demonstrate that shipping lines can enhance profitability through strategic partnerships with inland shipping companies, and Mclaughlin and Fearon (2013) analyze strategic cooperation and competition for ports driven by the increasing globalization and dynamics in the maritime area. More recently, the environmental benefits and the importance of collaboration in the transitions to renewable fuels are emphasized (Wang et al., 2024) .

Several reviews have looked at specific collaborative aspects in maritime and port transportation, such as shipping alliances (Ghorbani et al., 2022), empty truck trips (Islam, 2017), container repositioning (Kolar et al., 2018) and truck platoons based on automation (Bhoopalam et al., 2018).

Regarding decision-making, OR has provided significant support for collaborative transportation. Gansterer and Hartl (2020) provide an overview of the collaborative Vehicle Routing Problem (VRP) under the sharing economy paradigm. Guajardo and Rönnqvist (2016) give a summary of mathematical models used for cost allocation in collaborative transportation. More comprehensively and concretely, Cleophas et al. (2019) survey OR contributions on urban freight transportation, including the shared costs (or profits) allocation for incentivizing collaboration.

To the best of our knowledge, a comprehensive survey on collaborative maritime and port transportation does not exist. Although collaborative strategies have been suggested for decades, the research on methodologies for maritime collaboration is still disconnected. The recent developments in the collaboration of road transportation on the cusp of sharing trends motivate corresponding academic research is evolving in the maritime sector. This paper classifies dimensions of collaboration in the maritime shipping process and sheds light on OR methods for collaborative maritime and port transportation. We analyze how collaboration in maritime transport resembles or needs to be distinguished from problems in other domains of collaborative transportation. When modeling collaboration, it is important to consider the multi-sided market setting, 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. In this regard, we investigate the contribution of Game Theory (GT) to collaboration incentive and stability.

Following the logic of the different collaboration approaches, the remainder of this paper is organized as follows. Section 2 clarifies the scope of this paper by describing the dimensions of collaboration that happen in maritime freight transportation and introduces the methodology for searching papers. Section 3 details vertical types of collaborative maritime and port transportation, and Section 4 is for horizontal types. Section 5 summarizes the dominating methods in relation to the problems that they are applied to. Section 6 investigates the practical implementations of collaborative maritime systems, and Section 7 proposes an outlook on challenges for future OR research in supporting collaborative maritime shipping. Section 8 concludes the paper and emphasizes the key findings.

2. Scope and methodology

This section clarifies the scope of our survey and explains the methodology of collecting papers from the literature. Section 2.1 systematizes different dimensions of collaboration in maritime and port transportation, indicating how we organize the structure of the subsequent sections. Section 2.2 describes the reference searching and refining scheme.

2.1. *Dimensions of collaborative maritime and port transportation*

To make the significant body of literature on collaborative maritime and port transportation accessible to the reader, we intentively introduce collaboration types, stakeholders, collaboration objectives, and collaborative arrangements.

2.1.1. *Collaboration types*

We categorize the collaboration type based on the relative position of participating partners. Following Pomponi et al. (2013), there are two primary dimensions: vertical and horizontal. In vertical collaboration, players fulfilling different transportation roles coordinate to synchronize the flow of goods to enhance efficiency, such as integrating port operations with ship schedules. 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. This often means pooling resources and information, which requires strong incentives to encourage individual partners to collaborate. The challenges of planning in horizontal collaboration in transportation are often related to the routing of shared vehicles, the distribution of costs and profits, and the stability of the coalition.

2.1.2. *Stakeholders*

We further identify three primary stakeholders involved in collaboratively organizing maritime freight 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 paper, 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’ refers to the stakeholders responsible for orchestrating ship-port calling operations within this study. Distinctions between port operators and terminal operators will be explained when necessary. Additionally, other logistics (e.g., trucks, quay cranes, and yard cranes) service providers play a crucial role in connecting port or terminal operations with ocean shipping, and our survey also includes these decision-makers.

2.1.3. *Collaboration objectives*

Collaboration holds great promise in achieving the following ambitious objectives in freight maritime transportation. The first goal is efficiency improvement. Some existing works focus on evaluating the impact of collaborative planning on the profit of both individuals and the community (Soysal et al., 2018), which confirms that collaboration in freight transportation has the potential to improve market share and enhance profitability. The second is decarbonization. Whereas decarbonization in transportation remains challenging, there is excellent potential through shared infrastructure based on the application and further development of AI, simulation, and OR (Chen et al., 2017b). The third is resilience. Collaborative activities increase the system resilience via increased visibility, flexibility, and responsiveness (Scholten & Schilder, 2015). 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.

2.1.4. *Collaborative arrangements*

Collaborative arrangements can be understood as a progressive continuum, advancing from foundational communication & coordination

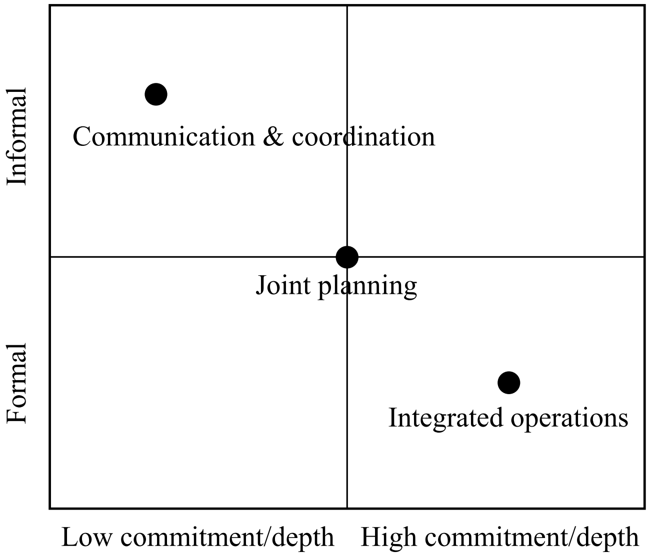

Fig. 1. Illustration of the collaborative arrangements in maritime and port transportation.

through more organized joint planning to fully developed, integrated operations, as shown in Fig. 1. Each stage along this continuum represents an increase in commitment, formality, and the potential for creating shared value. At its base, communication & coordination involve essential interactions and the sharing of basic information. As collaboration progresses to joint planning, partners align their operational activities, such as scheduling and resource allocation, which are typically governed by more formal agreements. In its most advanced form, integrated operations entail the sharing of assets, joint investments, or the establishment of joint ventures, all supported by comprehensive governance frameworks. Crucially, information exchange is not restricted to any one phase but functions as a foundational and pervasive enabler, expanding in scope, complexity, and strategic significance as collaboration deepens.

2.2. Search method

We employ a systematic search strategy to ensure a comprehensive and reproducible review of the literature on collaborative maritime and port transportation, following a multi-stage process shown in Fig. 2. The primary literature search was conducted using major academic databases, including Web of Science, Elsevier ScienceDirect, Scopus, and Google Scholar, which cover major journals in transportation and logistics science in the fields of maritime studies, operations research, and management science, among others. We searched 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. The following provides an overview of the keywords:

1. “maritime shipping”, “port collaboration”, “collaborative logistics”, “port cooperation”, “maritime supply chain”, “Port integration”, “terminal coordination”;
2. “vessel scheduling”, “berth and quay crane scheduling”, “Inter-terminal transport”, “drayage operations”;
3. “information sharing”, “digitalization”, “blockchain”, “IoT”, “smart port”;
4. “optimization”, “planning”, “decision-making”, “game theory”, “simulation”.

The scope of the review is restricted to publications written in English, with queries applied to titles, keywords, and abstracts. While the initial search is deliberately broad in scope, it is bounded by publication year from 2005 to 2025. This time frame is selected to capture the rise of systematic research into maritime collaboration, which accelerated with globalization, digitalization, and increased focus on supply chain resilience after the 2008 financial crisis. The search is limited to peer-reviewed journal articles; the selection criteria are further narrowed by focusing on studies that specifically address OR methods within the scope of collaborative maritime and port transportation (as illustrated in Fig. 3), deliberately excluding studies focused on hinterland transport. We review the titles and abstracts of the papers further to confirm alignment within the scope of the review. In the following refinement, we assess each study’s full text, prioritizing those employing well-defined OR models or quantitative approaches that are replicable and robust. Studies that lack sufficient methodological transparency or detail in their OR approach, or that solely provide qualitative assessments without methodological depth, are excluded from the final selection. Finally, we complement the list through a snowball approach, looking through references that papers in our list cite or that cite papers in our list. This additional search results in a final selection of 131 publications.

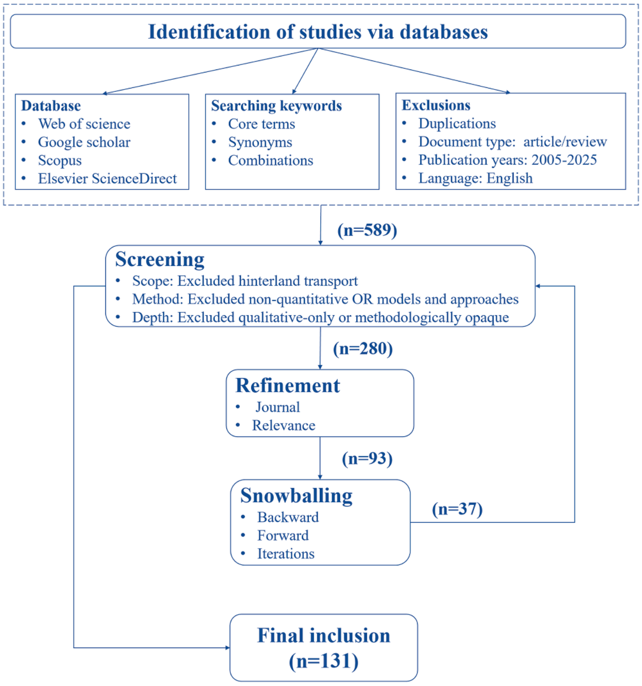

Fig. 2. Framework of the search method.

A summary of the relevant journals is presented in Table 1, showing journals with at least two relevant articles published. 20 journals are listed in total, and the most prominent journal is Transportation Research Part E: Logistics and Transportation Review (33 publications). Furthermore, the list is dominated by top-tier journals in Operations Research and Transportation, such as European Journal of Operational Research, Transportation Research Part A, B, C, D, E, and Transportation Science.

2.3. Rationale for the review framework

We organize the literature along four key dimensions: (i) the direction of collaboration, which examines the orientation of cooperative relationships, mainly including horizontal and vertical; (ii) the key stakeholders involved, identifying the primary actors engaged in collaborative efforts, such as shipping lines, port or terminal operators, and other transport or logistics service providers; (iii) the primary collaboration objectives, encompassing the strategic goals driving cooperative initiatives, including efficiency, decarbonization and

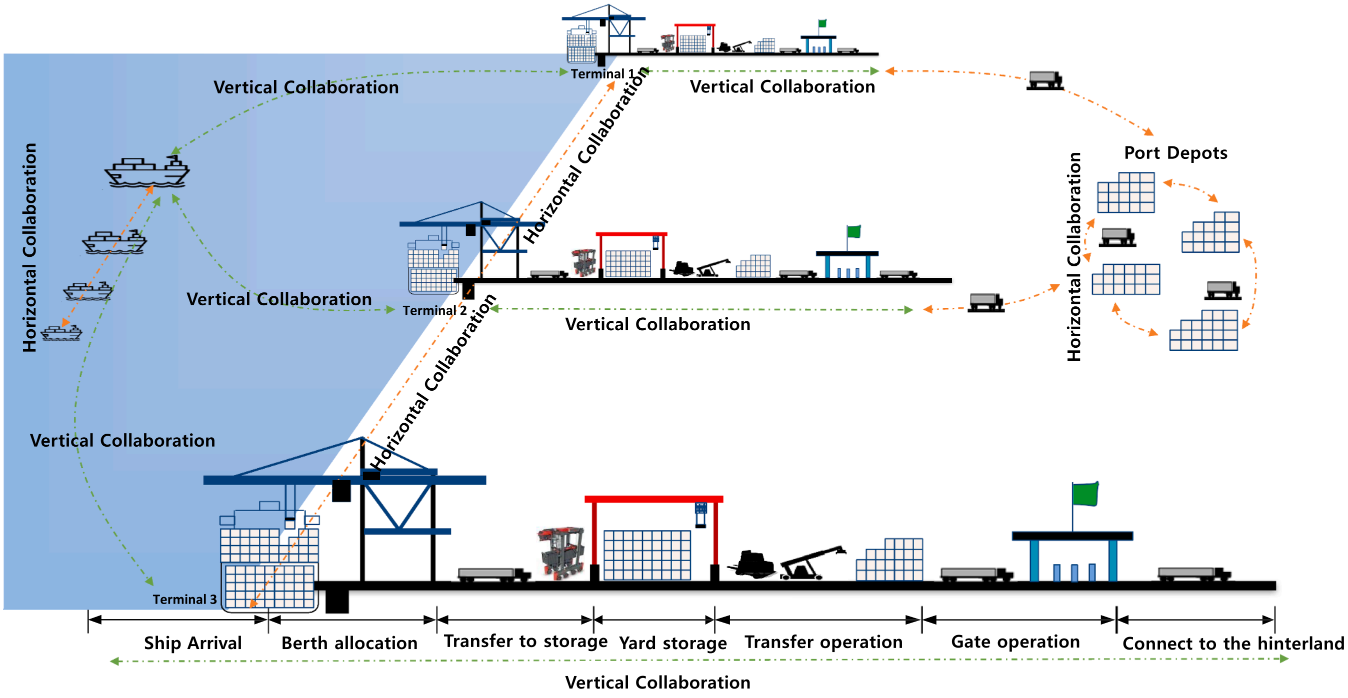

Fig. 3. Scope of collaborative maritime and port transportation in our survey.

Table 1
Journal lists with more than one relevant publication.

Journal Name	Number of Publications
Transportation Research Part E: Logistics and Transportation Review	33
European Journal of Operational Research	17
Transportation Research Part B: Methodological	13
Maritime Policy & Management	12
Transportation Research Part C: Emerging Technologies	8
Transportation Research Part D: Transport and Environment	5
Maritime Economics & Logistics	5
Computers & Industrial Engineering	5
Annals of Operations Research	4
Flexible Services and Manufacturing Journal	4
OR Spectrum	3
Transportation Science	3
IEEE Transactions on Intelligent Transportation Systems	3
Journal of the Operational Research Society	2
International Journal of Production Economics	2
Transportation Research Part A: Policy and Practice	2
Advanced Engineering Informatics	2
Journal of Marine Science and Engineering	2
Journal of Cleaner Production	2
Omega	2
The Asian Journal of Shipping and Logistics	2

resilience; and (iv) the collaborative arrangements, which captures explicitly the formal and informal mechanisms that enable cooperation, categorized into: information exchange (e.g., data sharing, visibility platforms), joint planning (e.g., synchronized scheduling, coordinated resource allocation), and integrated operations (e.g., shared assets, co-investment, joint ventures).

This framework is proposed because it addresses the fundamental questions of “how” (through direction and arrangements), “who”(stakeholders), and “why” (objectives) to collaborate, providing a comprehensive foundation for literature survey analysis. While other classifications (e.g., by methodology or region) are possible, this multidimensional approach captures the strategic, operational, and structural essence of maritime logistics collaboration, allowing us to holistically map the literature and identify research gaps at the intersections of these dimensions.

Fig. 3 conceptualizes the scope of our review of collaborative maritime and port transportation. Considering that many stakeholders can be involved in collaborative maritime and port transportation, we scope our survey within the collaboration during the transport process of sea shipping, port operations, and port drayage (e.g., from the depot to the terminal). Inland cargo transportation is outside the scope of our survey. Additionally, our research mainly examines container liner shipping unless otherwise specified, and the involvement with other types of cargo will be explicitly indicated in the context. Our survey on vertical and horizontal collaboration in freight maritime exhibits a critical aspect of promoting the Internet of Things (IoT) and PI in enabling superior performance and flexibility.

3. Vertical collaboration

Maritime transportation relies on a complex chain of interconnected operations, encompassing the sailing voyage 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 own activities independently. This operational independence can lead to inefficiencies from the supply chain perspective, compounded 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 it in the complex and large-scale maritime shipping industry takes time and effort. Therefore, in this section, we seek to answer the following questions by conducting the literature survey: (i) What forms of vertical collaboration are possible among stakeholders in freight 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 freight shipping into inter-port and intra-port processes. Inter-port operations pertain to vessel-to-port procedures involving sailing legs, vessel calls, and (un)loading vessels at terminals, while intra-port operations refer to multiple logistics activities to move cargoes within the port. Given this context, we

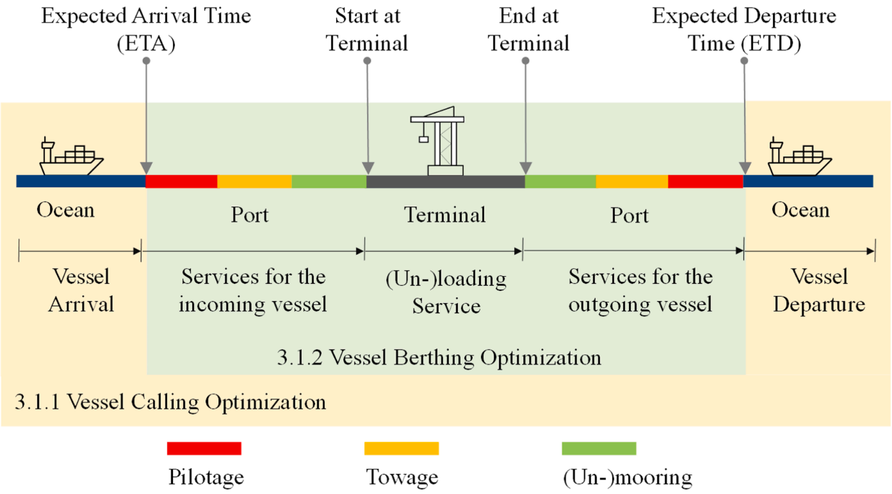

Fig. 4. Inter-port collaboration for vessel services.

categorize vertical collaboration into inter-port collaboration for vessel services in Section 3.1 and intra-port collaboration for cargo services in Section 3.2 correspondingly, and modeling and solution approaches are summarized in Section 3.3.

3.1. *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 carriers, which specialize 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-makers who arrange different vessel services (e.g., towage by tugboat or mooring by boatmen) before (un)loading vessels at the designated berth, referred to as port operators because the services are provided when the vessel is approaching terminals after arriving at the port.

Fig. 4 shows the process of vessel services at the port and how we frame the inter-port collaboration for vessel services into vessel calling optimization in Section 3.1.1 and vessel berthing optimization in Section 3.1.2. The shipping line decisions are usually interwoven with port and terminal operations. For example, the departure time at each port largely depends on the handling rate provided by terminal operators, which can directly affect the following legs and port of calls. However, the real world is not deterministic, and disruptions happen frequently; for instance, the arrived vessel spends extra time at the port waiting for the towage service because of port congestion. Such a delay at one port can propagate along the routes, leading to unnecessary losses and inefficiencies. Significantly, collaboration between the shipping line and port or terminal operators can provide promising solutions by cooperatively joining in the decision-making process of each other and thus fulfill better performance.

3.1.1. *Vessel calling optimization*

Research on vessel call and scheduling optimization can be broadly divided into (i) studies that focus on planning problems involving multiple stakeholders without mentioning deep collaboration mechanisms, and (ii) studies that treat multi-stakeholder collaborative planning as a central topic and design corresponding coordination mechanisms.

Multi-stakeholder planning without clarifying collaboration. Several studies incorporate port-side factors, such as berth occupancy, weather conditions, and tidal patterns, into vessel scheduling models to approximate Just-In-Time (JIT) port arrivals. For example, De et al. (2017) and Koza et al. (2020) develop multi-objective optimization frameworks that consider port availability when designing vessel schedules. Similarly, research on sailing speed optimization, such as Mulder et al. (2019), adjusts vessel speeds based on estimated port time windows or terminal capacity.

These studies acknowledge terminal operating conditions and incorporate them into vessel calling optimization through carrier decision-making. Although they do not dive into deeper collaborative frameworks, such as joint decision-making processes or incentive mechanisms between carriers and terminals, the multi-stakeholder optimization problems and models they develop remain highly valuable for understanding and advancing collaborative planning in the maritime shipping sector.

Collaborative planning as a central topic. One collaborative strategy allows shipping lines to select terminals based on individualized service criteria. Dulebenets (2022) propose a novel agreement in which carriers choose terminals according to preferences over time windows and handling rates. The authors develop a bi-objective optimization model balanced for cost and emissions and introduce an exact solution method, moving beyond metaheuristics to provide scalable and exact decision support for such collaborative settings. Another strategy involves the joint determination of handling rates. Traditionally set unilaterally by terminals, handling rates can be bilateral under collaboration. Liu et al. (2016) design a mechanism where shipping lines pay premium fees for higher handling rates. Their results demonstrate significant fuel savings for carriers with only a moderate increase in terminal service fees. Wang et al. (2015b) adopt a similar approach but incorporate utility estimations from carriers and terminal operators, ensuring mutual gains from collaboration.

Further studies integrate vessel scheduling with broader operational decisions. Zhao et al. (2022) combine bunker management with vessel scheduling, enabling shipping lines to optimize sailing speeds while considering terminal status and refueling plans. Reinhardt et al. (2016) aim to minimize total bunker consumption across a network by rescheduling port calls, introducing constraints on the number of rescheduled visits to balance efficiency with practical feasibility. Alharbi et al. (2015) incorporate container inventory decisions into vessel scheduling, with terminals providing time windows based on systematic handling efficiency. Wang et al. (2014) simultaneously optimize container allocation and vessel schedules, capturing both shipping and demurrage costs associated with port waiting times.

These research places collaboration at the core of the planning process, creating integrated decision-making frameworks that benefit multiple parties.

3.1.2. Vessel berthing optimization

Coordination of pre-services. Various services, including pilotage, towage, and mooring, are provided by different port departments before berthing at one terminal and must be readily available once a vessel arrives at the port (Nikghadam, 2023). These pre-services have to be counted as part of the berthing process. Inefficient service connections between them can cause extra waiting time and correspondingly increase vessel turnaround time at the port. Talley et al. (2014) state that a cooperative port service chain is more effective than non-cooperative cases. Nikghadam (2023) model the information exchange between the port's pilotage and towage service departments. They apply the model to the case of the Port of Rotterdam, finding waiting time savings of up to 30%. Kasm et al. (2021) consider pilotage and tug operations simultaneously to schedule vessel movements within the port before berthing operations.

Collaboration in berth allocation problem (BAP). BAP is one of the most critical decisions of terminal operators for each port call to decide when and where to (un) load the vessels, and it 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 vary in the collaborative setting. Golias et al. (2009b) first propose a BAP model to minimize the total waiting and delayed departure time for all vessels by treating the vessel arrival time as a variable. This approach enables terminal operators to offer a preferred calling time from the perspective of better optimizing the cargo handling process, and shipping lines can also benefit from less idle time at the terminal simultaneously. Golias et al. (2009a) and Du et al. (2011) propose an enhanced BAP model that allows terminal operators to offer calling time windows to shipping lines.

Collaborative BAP. Extending the scope of collaboration, Venturini et al. (2017) develop a MIP model for the multi-port BAP, aiming to minimize the costs of all terminals along the entire shipping route. Wang et al. (2015b) incorporate a utility-based compensation mechanism into their collaborative berth allocation model, where higher bunker and inventory costs decrease the utility of shipping lines. Terminal operators are compensated based on the initial utility estimated by shipping lines. Conversely, shipping lines are also compensated if their expectations are not satisfied. Building on the earlier work on the multi-port BAP, Song et al. (2024) investigate allocations considering vessel speed optimization using a MIP model and Variable Neighborhood Search (VNS). The authors confirm the assumed benefits of integrated speed optimization, under the condition that time windows are respected.

Yard container stowage. One indirectly relevant research area is yard container stowage. According to the stowage plan shipping lines provide, terminal operators organize yard cranes to load containers to the calling vessels from the container yard and vice versa. Due to the limited access of yard cranes to only the topmost containers, container relocations happen frequently within the yard (Tanaka & Voß, 2019). 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 (Ambrosino & Sciomachen, 2003). Thus, terminal operators need to coordinate yard container stacking and shipping lines' vessel stowage plans. Junqueira et al. (2022) extend the model into a multi-port setting, designing a simulation-optimization method and rule-based heuristics to obtain the solution. In the context of cooperative agreements between terminal operators and shipping lines, Iris et al. (2018) define a flexible ship loading problem 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. Bilican et al. (2024) even consider the preceding step of cargo composition, proposing a collaborative bi-level programming approach and observing significantly increased revenue based on the proposed collaborative framework.

3.2. 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, and Inter Terminal Transportation (ITT) is unavoidable. This part focuses on studies related to vertical collaboration within the context of intra-port collaboration, while horizontal collaboration will be discussed in Section 4. Three types of vertical intra-port collaboration for cargo vessels are identified: coordination of multiple transport processes in Section 3.2.1, synchronization of ITT in Section 3.2.2, and the port gate control and Truck Appointment System (TAS) in Section 3.2.3. For convenience, we refer to trucks that move within the yard area as internal trucks, and those transporting from depots to the terminal or vice versa are external trucks.

Fig. 5 illustrates the detailed intra-port cargo transport process, and it also shows the structure of this part. 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. Inland transportation is outside the scope of this study, as we only consider the transportation process of passing through the port's gate and within the port. Effective coordination is important due to the involvement of multiple logistics activities.

3.2.1. Coordination of multiple transport processes

A vast number of papers published in OR journals focused on studying the integrated planning problem occurring on the land side of the port, such as berth allocation and quay crane scheduling (Iris et al., 2015; Meisel & Bierwirth, 2013; Türkoğullarıet al., 2016; Xie et al., 2019), berth and yard template for deterministic setting (Jin et al., 2015) and uncertain considerations (Zhen et al., 2022), crane and yard truck scheduling (Gao & Ge, 2022; Hop et al., 2021; Zhen et al., 2019) synchronization of multiple handling facilities from the perspective of the whole terminal (Cahyono et al., 2021; Kizilay et al., 2020; Liu et al., 2022).

Advanced handling facilities. Kong et al. (2021) investigate the container operation by coordinating Tandem Quay Cranes (TQCs) with internal truck scheduling. 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. Kasm et al. (2022) consider the type of next-generation cranes that can provide services from both sides of the vessel and catch four containers at a time. For ports in the transition phase from traditional cranes to the new type, they develop a joint scheduling model of two types of cranes.

Automation technology. Luo et al. (2016) study the integrated scheduling of Quay cranes (QCs), Yard Cranes (YCs), and Automated Guided Vehicles (AGVs) at a partial automatic container terminal layout. Their study only aims at examining the vessel loading process, while Li et al. (2020) further incorporate both loading and unloading processes, reflecting more realistic characteristics of the automated container terminals. Shouwen et al. (2021) consider a new synchronous loading and unloading mode where the equipment loads or unloads two containers during a round-trip operation. To optimize this process, the authors formulate a bi-level programming model. The upper model is the joint scheduling model of container handling facilities (e.g., QC and AGV) to minimize the maximum makespan of moving all containers, and the lower model is the path plan aiming to minimize the travel distance of AGV.

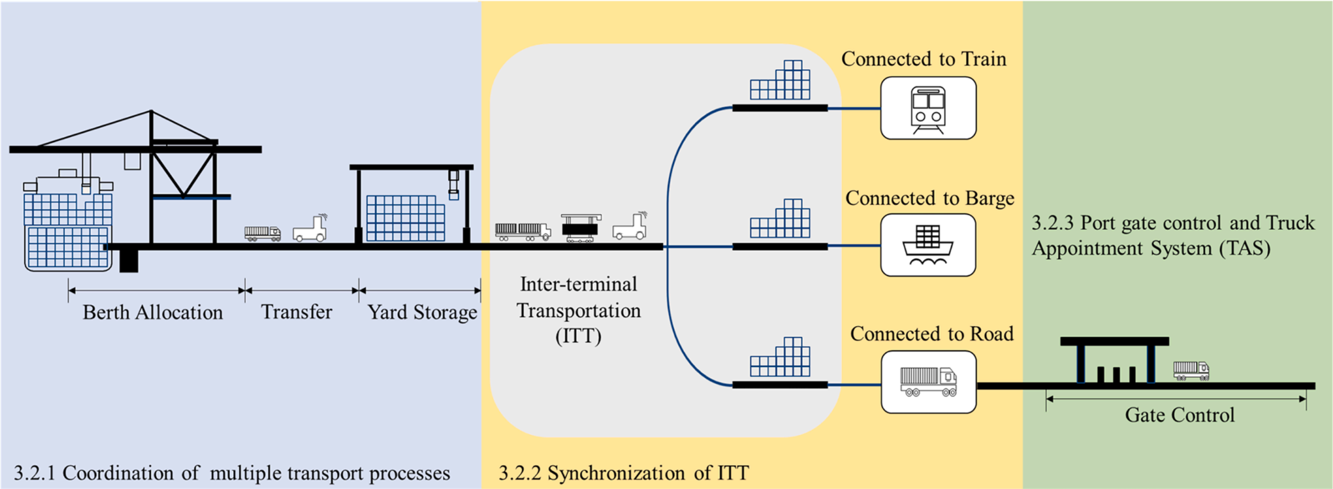

Fig. 5. Intra-port collaboration for cargo services (based on Imo (2016)).

3.2.2. *Synchronization of ITT*

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 dramatically motivates the ITT research regarding moving containers and cargo between organizationally separated terminals within a port (Heilig & Voß, 2017). We focus 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-train, sea-barge, and sea-road intermodal transportation.

Sea-train. Aisha et al. (2022) study the terminal layout for the port to reduce transport distances between the quay and the rail tracks, reducing the ITT cost of sea-rail transportation. Chang et al. (2019) coordinate ITT container handling operations for sea-rail intermodal transportation. The authors formulate a MIP model and design a multi-layer GA heuristic to solve the optimization model. The study highlights the importance of coordinating internal trucks, gantry cranes, and yard cranes in achieving efficient inter-terminal sea-rail internal operations. Hu et al. (2018) explore methods for optimizing the dispatch of ITT vehicles that move cargoes between terminals and train schedules at railway terminals. The objective is to minimize operational and delay costs for containers. Nuzuri et al. (2022) seek to enhance intermodal planning by incorporating the scheduling of vessel arrival and train departure to facilitate seamless connections. Yan et al. (2020) construct a MIP model to facilitate the integrated planning of train schedule templates and container transshipment operations. Notably, the authors identify certain variables within the model that can be relaxed without compromising the optimal solution. Additionally, they propose a set of valid inequalities to strengthen the constraints and enhance the efficiency of solving the model.

Sea-barge and sea-road. Lee and Jin (2013) present a study on container transshipment terminals by integrating the berth and yard allocation with the schedule of the mother and feeder vessels to reduce unnecessary ITT. More comprehensively, Schepler et al. (2017) aim to minimize the turnaround time of containers and reduce unnecessary ITT by optimizing the schedules of connecting ships, trains, and trucks. The authors developed a MIP model that focuses on selecting container terminals for feeder vessels and barges and determining the stops for trains. In addition, Kolar et al. (2018) review the effectiveness of intermodal transportation in empty container repositioning problems, and the review of Bu and Nachtmann (2021) focus on the connection of sea-barge transportation.

3.2.3. *Port gate control and TAS*

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, TAS has been widely accepted as a practical solution, which is used to manage external truck arrivals and balance it with the internal workload of the port based on collaboration between the terminal operator and truck companies. Many studies highlight the importance of efficient truck management in mitigating port gate congestion and enhancing environmental sustainability, providing evidence for supporting the TAS in the port.

Allocating truck time slots. Namboothiri and Erera (2008) study the arrival scheduling problem of external trucks via TAS to assist terminal operators in deciding the optimal number of trucks to accept during some periods. Chen et al. (2013) propose a truck management strategy that optimizes the time window allocated to truck groups by terminal operators. The approach utilizes a non-stationary queueing model to estimate the queue length. It employs several GA-based meta-heuristics to minimize the total system cost, including the waiting time of trucks, idling fuel consumption, cargo storage time, and storage yard fee. Zhang et al. (2019) also study appointment quota plans by analyzing the truck queuing pattern. Specifically, they consider the coordination of internal trucks, yard cranes, and external trucks.

Advanced scheduling methods to handle complex operations. Sun et al. (2022) explore the data-driven approach to extracting valuable insights regarding the interplay between a truck's arrival and its turnaround time at a given terminal. Then, based on the findings, they formulate a robust optimization model for truck quota assignment of TAS. Mar-Ortiz et al. (2020) propose an optimization-based decision support system (DSS) for managing truck arrival bookings at a port. The system optimizes the appointment quota for each time slot on a one-day horizon, considering yard resource availability and workload coordination. Gracia et al. (2017) explore the effects of implementing a booking system to reduce port gate congestion by flattening truck arrival times. The study examines the impacts of lane segmentation strategies and booking levels on congestion levels. Torkjazi et al. (2018) considers minimizing trucks' deviation from their original schedule when allocating the arrival time window via TAS. Im et al. (2020) introduce a TAS model for the truck turnaround process that simultaneously incorporates truck waiting time and container rehandling time.

Balancing peak and off-peak periods. Li et al. (2022a) present a novel queuing model designed to estimate the queuing length for scheduling truck appointments at a dual-transaction container terminal system. In such a system, external trucks drop off one container and pick up another on a single trip, making the coordination of handling equipment for pick-up and delivery a critical factor that significantly impacts the turnaround time of trucks. Phan and Kim (2015) present a decentralized mathematical model to optimize the balance of the truck arrival between peak and off-peak hours. This model assists the negotiation process between multiple truck companies and the terminal. In their subsequent work of Phan and Kim (2016), the authors enhance the model by involving sub-problems of truck scheduling for each truck company. Truck companies can update their appointment applications in their studies, and the terminal responds in real-time, making the model more practical.

Empty container management. Yi et al. (2014) investigate the issue of empty container transport in the context of a collaborative strategy between terminal operators and truck carriers. Yu et al. (2018) utilize a two-stage game model to investigate the interaction between the terminal operators and the truck companies in managing empty containers. In the first stage, the terminal operator announces the free detention time. In the second stage, the truck dispatching operator determines the optimal arrival time to transport the empty container back to the terminal, balancing transport costs and detention fees. Zehendner and Feillet (2014) make the truck appointment plan by coordinating ITT vehicles with the external truck arrival. The authors use TAS to streamline terminal operations and enhance the overall service quality. In addition, terminal operators can make better stacking plans to minimize the container rehandling based on the truck announcement, see Asperen et al. (2013) and ŕez Nafarrate et al. (2017).

3.3. *Critical evaluation of the modeling and solution methods in vertical collaboration*

To summarize, we offer a comprehensive overview of research studies focused on vertical collaboration in maritime and port transportation. The following analysis organizes these papers according to key aspects, including the associated decision problems, the special considerations highlighted in each study, the primary objectives, the modeling approaches, and the solutions. This categorization provides a clear understanding of how different research efforts tackle vertical collaboration across various contexts, helping to identify patterns and trends in the literature. The Table 2 serves to present these studies in a structured format for easier comparison and deeper insight.

MIP is the most frequently applied modeling approach, widely used in berth BAP, TVS, and TAS. MINLP is also used, particularly in VScO and VSP, where there are nonlinear relationships between decision variables. Other advanced modeling techniques, such as SDP and MOP, are applied to tackle uncertainty and multi-criteria decision-making scenarios, especially in collaborative and environmentally focused optimization problems.

In terms of solution methods, heuristic algorithms and solver-based approaches dominate the landscape. Heuristic techniques, including genetic GA, Tabu, ALNS and VNS, are prevalent for their ability to provide near-optimal solutions in complex and large-scale problems. These methods are particularly effective in problems requiring flexibility, such as berth allocation, truck scheduling, and ITT. Solver-based approaches, such as LI, CS, and CG, offer precise solutions, although their scalability may be limited in large problem instances.

Moreover, emerging solution and modeling approaches such as MPA and CGT highlight the growing integration of intelligent decision-making models in maritime logistics. QO and GO have been adopted in emission-related optimization problems, demonstrating a shift towards sustainability-focused decision frameworks.

Overall, the field of vertical collaboration in maritime and port operations has seen significant advancements in OR modeling and solution methodologies. However, the trade-off between solution accuracy and computational efficiency remains a key consideration. Future research should focus on hybrid approaches that combine exact and heuristic methods to enhance scalability and robustness, ensuring efficient and adaptive decision making in dynamic maritime environments.

4. Horizontal collaboration

Horizontal collaboration in maritime freight transportation involves multiple stakeholders from the same level of the transport chain. Based on the participants involved, we identify three conventional forms: shipping alliances formed by shipping lines, terminal collaboration formed by terminal operators, 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 transport vehicles to maximize capacity utilization. In this section, we survey these three forms of horizontal collaboration and analyze innovations in light of digital and autonomous transformations.

A series of crucial decisions are faced by involved participants in horizontal collaboration. First, they need to decide whether to join the collaboration, or sometimes this problem equals selecting a coalition to join or selecting partners to form a coalition. Second, they must formulate collaborative agreements to optimize shared resource and capacity sharing and distribution. Third, a reasonable mechanism to share costs or profits is necessary, which will also influence the formation of collaboration. Following this logic, we organize the following three part subsections: the formation of collaboration in Section 4.1, the optimization of shared capacity in Section 4.2, and shared costs or profits allocation in Section 4.3. Finally, we summarize the modeling and solution approaches in Section 4.4.

4.1. *The formation of collaboration*

The idea of horizontal collaboration is that participants can cooperate to provide service to leverage the potential economies of scale (Álvarez Sanjaime et al., 2013). We report the relevant studies in Table 3, and we organize the structure as partner selection and co-opetition analysis in Section 4.1.1 and motivation establishment in Section 4.1.2.

4.1.1. *Partner selection*

At the formation stage, selecting a coalition or partners is important, which decides whether the collaboration is established directly. There are some empirical studies on partner selection standards for shipping alliances (Solesvik & Westhead, 2010) and port collaboration (Chen et al., 2015). However, in certain situations, competitors may also engage in collaborative efforts. Since Midoro and Pitto (2000) outlined internal competition as the key factor that adversely affects the level of mutual trust within shipping alliances, strategic analysis of competition and cooperation dynamics have been widely studied. This is known as co-opetition as defined by Song (2003) and can be seen in shipping alliances (Song et al., 2021), port or terminal coalitions (Budipriyanto et al., 2015; Kavirathna et al., 2019). Specifically, facing the increasing bargaining power of shipping alliance, Zheng and Luo (2021) investigate the port's optimal competitive strategies reacting to the shipping market.

4.1.2. *Motivation establishment*

Establishing motivation is essential for stakeholders to collaborate. Some papers focus on quantitative comparisons with and without joining the coalition, showing the potential benefits of collaboration. Qiu et al. (2018) investigate the relationship between vessel-sharing strategy and environmental performance along the Belt and Road maritime route. The authors develop two MIP models to decide fleet deployment and container allocation under two scenarios, with and

Table 2
An overview of vertical collaboration in maritime and port operations.

Reference	Problem	Special consideration	Collaborative Arrangement	Objective	Modeling Approach	Solution Approach
Golias et al. (2009b)	BAP	Optimizing vessel arrival time	IO	Cost	MIP	H:GA
Lee and Jin (2013)	TVS, BAP	Feeder vessel arrival time	IO	Cost	MIP	H:GA, H:Tabu
Zhao and Goodchild (2013)	TAS-impact	Container retrieval and rehandle operation	JP	Cost	SM	Solver
Chen et al. (2013)	TAS-TAT	Gate congestion	IE, JP	Cost	MIP	H
Zehendner and Feillet (2014)	TAS-TVS in ITT	Multimodal (train,truck,barge)	JP	Cost	MIP	Solver:Cplex
Wang et al. (2015b)	BAP	Utility setting and compensation	JP	Utility	MIP	Solver
Wang et al. (2015a)	VScO	Cargo demurrage	IE, IO	Profit	MINLP	LI, Solver:Cplex or Gurobi
Jin et al. (2015)	BAP	Workload balance in peak-off hours	IO	Cost	MIP	CG
Liu et al. (2016)	VSpO	Flexible handling rates and compensation	JP	Cost	MINLP	KKT
Luo et al. (2016)	TVS, YAP	Automated terminal	IO	Time	MIP	H:GA
Phan and Kim (2016)	TAS-TruS	Interacting with terminal operation	JP	Cost	MIP	Solver:Cplex
Reinhardt et al. (2016)	VSpO	Balance the slow steaming for round trip	IO	Cost	MINLP	DC
Venturini et al. (2017)	BAP	Optimizing vessel arrival time	IO	Cost, emission	MIP	Solver:Cplex
Gracia et al. (2017)	TAS-impact	Lanes segmentation and booking levels	JP	Cost	SM	Arena
ŕez Nafarrate et al. (2017)	TAS-impact	Container retrieval and rehandle operation	JP	Cost	SM	H
Dulebenets (2018)	VScO	Multiple TWs & HRs offered by terminals	IE, JP	Cost	MINLP	LI, Solver:Cplex
Hu et al. (2018)	TVS in ITT, TraS	Connected with railway	IO	Cost	MIP	H:Tabu
Iris et al. (2018)	TVS	Coordinating transferring vehicles	IO	Cost	MIP	H
Mulder et al. (2019)	VSpO	Buffer time	IO	Cost	SDP	SGD
Chang et al. (2019)	TVS, YAP in ITT	Connected with railway	IO	Time	MIP	H:GA
Li et al. (2020)	TVS,YAP	Automated terminal	IO	Cost	MIP	H:GA
Kasm et al. (2021)	VBO	Multiple port-call process	IO	Delay	MIP	CS
Cahyono et al. (2021)	TVS	Real-time information update	IO, JP	Cost	DP	MPA
Kong et al. (2021)	VSP, TVS	Tandem quay cranes	JP	Cost	MILP	H
Shouwen et al. (2021)	TVS	AGV conflict free	JP	Time	MIP	H
Sung et al. (2022)	VSpO	Coordinating vessels towards the same terminal	JP	Time, emission	SM, QO	Solver:IpOpt
Dulebenets (2022)	VScO	Interactive TWs & HRs between terminals and shipping lines	IE, JP	Cost, emission	MOP	ϵ, GO
Martin-Iradi et al. (2022)	BAP	Optimizing vessel travel speeds between multiple ports	IE, IO	Cost	MIP, CGT	B&C&P
Zhang et al. (2022b)	VBO	Multiple port-call process with channel restriction	IO	Cost	MILP	H:VNS, NSGA-II
Zhu (2022)	VSP	Terminal yard operation	IO	Cost	NLP	H
Zhen et al. (2022)	BAP, YAP	Uncertainty	IO	Cost	SP	CG
Kasm et al. (2022)	TVS	Combined new and old cranes	IO	Cost	MIP	CG, SuT
Nuzuri et al. (2022)	VScO , TVS in ITT	Coordinating vessel arrival and train schedule	IO	Time	MIP	H
Nikghadam et al. (2023)	VBO	Multiple port-call process	JP	Cost	SM	Anylogic
Martin-Iradi et al. (2024)	BAP	Continuous BAP	IE, JP	Cost	MIP	H:ALNS

Note: **Problem:** VSpO: Vessel Speed Optimization; VScO: Vessel Schedule Optimization; VBO: Vessel Berthing Optimization; BAP: Berth Allocation Problem; VSP: Vessel Stowage Plan; YAP: Yard Allocation Problem; TVS: Transport Vehicle Schedule; ITT: Inter-Terminal Transportation; TraS: Train Schedule; TAS: Truck Appointment System; TAT: Truck Arrival Time; TruS: Truck Scheduling; **Collaborative Arrangement:** IE: Information Exchange; JP: Joint Planning; IO: Integrated Operation;**Modeling Approach:** SM: Simulation; QO: Quadratic Optimization; SDP: Stochastic Dynamic Programming; MINLP: Mixed Integer None Linear Programming; MOP: Multi-Objective Programming; MIP: Mixed Integer Programming; NLP: None Linear Programming; SP: Stochastic Programming; DP: Dynamic Programming; MILP: Mixed Integer Linear Programming; CGT: Cooperative Game Theory; **Solution Approach:** SGD: Sub Gradient Decent; LI: Linearization; ϵ: ϵ-constraint Method; GO: Goal Programming; DC: Discretization; CS: Constraint Separation; H: Heuristics; VNS: Variable Neighborhood search; ALNS: Adaptive Large Neighborhood Search; NSGA-II: Non-dominated Sorting Genetic Algorithm II; GA: Genetic Algorithm; CG: Column Generation; MPA: Model Predictive Algorithm; SuT: Speed Up Technique; Tabu: Tabu Search; B&C&P: Branch-and-Cut-and-Price;

without vessel sharing, and the experimental results indicate significant profit enhancement and emission mitigation. Irannezhad et al. (2018) further examine the advantages of a vessel-sharing strategy in quantitatively improving empty container reuse and reducing drayage costs. Pujats et al. (2021) analyze the dynamics of terminals' individual profit and their willingness to cooperate. Wong et al. (2018) conduct empirical research on facilitating terminal coalitions at the Hong Kong Port, consisting of five terminal operators. Kim et al. (2022) 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 enter the coalition. According to Rau and Spinler (2016), 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 Rau and Spinler (2017), they further consider low profitability and frequent alliance changes by developing a simulation model. Liu et al. (2018) propose a game-theoretical model to investigate the strategic investment strategy of disaster prevention for multiple ports in the same region. They find that cooperation between complementary ports results in a higher investment level, which subsequently reduces the probability of disruptions. Asadabadi and Miller-Hooks (2018)

Table 3
Relevant studies on the formation of horizontal collaboration.

	Problem	Alliance			Reference
		S	P	T	
Partner selection	Selection standards	✓			Ding et al. (2005), Solesvik and Westhead (2010)
			✓		Chen et al. (2015)
	Competition and cooperation	✓			Lin et al. (2017), Song et al. (2021)
				✓	Budipriyanto et al. (2015), Kavirathna et al. (2019), Saeed and Larsen (2010)
			✓		Li and Oh (2010), Yap and Lam (2004)
Motivation establishment	Quantative comparison with and without collaboration	✓			Irannezhad et al. (2018), Qiu et al. (2018)
				✓	Kim et al. (2022), Pujats et al. (2021), Wong et al. (2018)
	Collaborative investment	✓			Rau and Spinler (2016, 2017)
			✓		Asadabadi and Miller-Hooks (2018), Li et al. (2022b), Liu et al. (2018)

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

investigate the resilience of ports in the face of disasters. The study focuses on two levels: The higher level aims to analyze the co-opetition among ports, in which each port makes protective investments based on predictions of other ports' responses. The lower level is modeled as a cost-minimization problem, considering the gains and losses caused by other ports' decisions. Li et al. (2022b) propose an approach for improving port resilience through cross-port investments and capacity sharing in port collaboration. A Stackelberg equilibrium is designed to ensure the best investments given market competition. Reasonable profits or cost-sharing can also incentivize the formation of collaboration, and we will discuss this specifically in Section 4.3.

4.2. The optimization of shared capacity

While forming alliances in the whole transportation industry is recognized as a promising strategy, operating such a collaborative system effectively and efficiently presents significant challenges. It requires careful planning models supported by both technical and regulatory aspects. Furthermore, the changing market demands alliances to be flexible and adaptive, which increases the difficulty of planning optimization. Consequently, many OR papers focused on optimizing shared capacity to maximize resource utilization.

Given that various collaboration forms in maritime freight transportation have distinct decision-making characteristics, we introduce collaborative models categorized by the forms of horizontal collaboration: shipping alliance in Section 4.2.1, port collaboration and terminal coalitions in Section 4.2.2, and container drayage collaboration in Section 4.2.3. For each form, we present the surveyed papers and report the optimization problem, special consideration, shared resources, goals to achieve and approaches in Table 4.

4.2.1. Shipping alliances

Slot allocation. A shipping alliance is a group of ocean carriers that work together 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. Chen et al. (2017a) develop an IP model 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. The study only applies the model to a small-scale instance that involves two routes operated by two carriers. Chen et al. (2022a) extended this work by proposing a multi-objective mathematical model that simultaneously maximizes total revenues and vessel capacity utilization. Wong et al. (2022) propose a three-echelon collaborative slot planning model for multiple routes. Specifically, the authors consider cargo-shifting operations among multiple routes to improve slot usage and overall yields.

Integrated decisons. Ambrosino and Sciomachen (2021) 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. Mandal et al. (2022) propose a multi-agent framework for container booking and slot allocation, in which real-time information is interchanged within the alliance. In addition, Ng (2017) revises the liner fleet deployment model based on the vessel sharing agreement. Jiang et al. (2013) and Yu et al. (2022) investigate the shared-yard space allocation and management problem.

Enhancing relevant planning. The slot and container sharing strategy opens opportunities for improving other relevant planning problems. Wetzel and Tierney (2020) propose a novel MIP model to address the liner shipping fleet deployment and repositioning problem, enabling shipping alliances to establish flexible shipping networks in response to fluctuations in market demand and seasonal changes in the global economy. Wong et al. (2021) study the fleet repositioning problem by incorporating the optimization of freight rates and port selection to achieve maximum utility in revamping services. Their model 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, Lei et al. (2008) study the vessel scheduling problem under the slot-sharing agreements among carriers. They propose a simplified model that can be managed by MIP, ignoring carriers' individual concerns, such as cargo types and priority. However, the study highlights that potential cost savings depend on the partner carriers' willingness to engage in full collaboration. Reinhardt et al. (2020) optimize the shipping networks by rescheduling the port call times. They differentiate their approach from traditional vessel scheduling by accounting for vessel-sharing agreements and the coordination of feeder vessel services. Additionally, container sharing among carriers provides better solutions for empty container repositioning, see the work of Lin and Juan (2021).

Vessel train. With the emergence of autonomous technology, the vessel train concept has been created as a new type of collaboration in the shipping alliance. Typically, the vessel train comprises one leader vessel and several follower vessels that are virtually linked to move 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. For measuring the economic performance of the vessel train with conventional sailing, Meersman et al. (2020b) first identify the main cost performance indicators to evaluate the performance of

Table 4
Optimization of shared capacity appearing in horizontal maritime collaboration.

Alliance	Reference	Problem	Special consideration	Shared resources	Goal	Approach
SA	Lei et al. (2008).	VSO	Slot-exchange vs. total sharing	Vessel space	Cost	MIP, H
	Chen et al. (2017a).	VSA	Co-chartering agreement	Vessel space	Profit	IP, Solver: LINGO
	Chen et al. (2018).	VTS	Cooperative multi-vessel system	Navigating information	Cost	MPC, Solver:Matlab, Cplex
	Wetzel and Tierney (2020).	FSN	Integrated fleet deployment and repositioning	Vessels	Profit	MIP, H
	Reinhardt et al. (2020)	VSO	Multiple practical business constraints	Vessels	Cost	MIP, Solver:Cplex
	Meersman et al. (2020a)	VTS	Positive impact on cost, time and emission	Vessels	Cost	-
	Ambrosino and Sciomachen (2021).	SP, VSA	Hazardous goods	Vessel space	Cost	MIP, H
	Chen et al. (2022a).	VSA	Slot exchange	Vessel space	Profit	MOP, H: NSGA-II
	Wong et al. (2021, 2022)	VSA	Three-echelon	Vessel space	Profit	MIP, B&B, GA, DNN
	Yang et al. (2023).	VTS	In a hub-and-spoke network	Navigating information	Cost	MINLP, LI, Solver: Cplex
TC	Lalla-Ruiz et al. (2015).	BAP	Decentralized collaboration by grouping individuals	Terminals	Cost	MIP, H
	Ma et al. (2020).	BAP	Centralized sharing vs decentralized sharing	Terminals	Cost	MIP, Solver:Cplex
	Yang et al. (2020).	TVA	Sharing facilities among multiple terminals	Trucks	Cost	MIP, MOP, H
	Cho et al. (2021).	BAP	Allow for reassignment of vessels to other terminals	Terminals	Cost	MIP, H
	Lyu et al. (2022).	BAP	Disruption recovery	Terminals	Cost	MIP, H
	Lyu et al. (2025).	BAP	Fair cost allocations as collaboration incentives	Terminals	Cost	MIP, CGH, RG
CDC	Zhang et al. (2010)	TS	Four types of container movement requests pooling	Trucks	Time	MIP, Solver: LINGO
	Braekers et al. (2013)	TS	Integrated loaded and empty containers	Trucks	Cost	MIP, H
	Lai et al. (2013).	TS	Heterogeneous trucks with backhauls	Trucks	Cost	MIP, H
	Sterzik et al. (2015).	TS	Integrating with empty container repositioning	Empty containers	Time	MIP, H:Tabu
	Xue et al. (2015, 2014).	TS	Separation of tractors and trailers	Empty containers	Cost	MIP, H
	Schulte et al. (2017).	TAS-TS	Conduct services not associated to their own truckers	Trucks	Cost, emission	MIP, Solver: Cplex
	Shiri and Huynh (2018).	TS	Treating tractor, chassis, and container as separate resources	Trucks, empty containers	Cost, emission	MIQP, H
	You et al. (2020)	T-PS	Considering both trucks' cost and drivers' cost	Trucks	Cost, emission	MIP, H
	Chen et al. (2021).	T-PS	Container transshipment, platooning and speed optimization	Autonomous trucks	Cost	MISOCP, H
	Yan et al. (2023).	T-PS	Freely form platoons with by autonomous technologies	Autonomous trucks	Cost	MIP, H
	Pourmohammad-Zia et al. (2023).	AGV-PS	Heterogeneous vehicle network	AGV, trucks	Cost, time, emission	MIP, RO, ϵ, Solver: Cplex
	Fazi et al. (2023).	TS	Availability of empty containers and shippers' time windows	Empty containers	Cost	MIP, C&R-G

Alliance: SA: Shipping Alliance; TC: Terminal Collaboration; CDC: Container Drayage Collaboration; Problem: SP: Stowage plan; VSA: Vessel Slot Allocation; FSN: Flexible Shipping Network; VSO: Vessel Speed Optimization; VTS: Vessel Train Scheduling; BAP: Berth Allocation Problem; TVA: Transport Vehicles Allocation; TS: Truck Scheduling; TAS: Truck Appointment System; T-PS: Truck Platooning Scheduling; AGV-PS: Automated Guided Vehicle Platooning Scheduling; Approach: MIP: Mixed Integer Programming; IP: Integer Programming; MINLP: Mixed Integer None Linear Programming; LI: Linearization; MOP: Multi-Objective Programming; H: Heuristics; GA: Genetic Algorithm; Tabu: Tabu Search; NSGA-II: Non-Dominated Sorting Genetic Algorithm II; B&B: Branch and Bound; DNN: Deep Neural Network; MPC: Model Predictive Control; CGH: Cooperative Game Theory; RG: Row Generation; C&R-G: Column and Row Generation; MIQP: Mixed-Integer Quadratic Programming; MISOCP: Mixed-Integer Second-Order-Cone Programming; RO: Robust Optimization; ϵ: ϵ-constraint method;

the vessel train transport system. Then, in the later work of Meersman et al. (2020a), they analyze the inland trajectory Antwerp-Rotterdam-Duisburg, and the results show that the vessel train offers lower overall fixed costs. The authors estimate that the vessel train can bring about 23.04% to 41.57% cost reductions within a 10-year horizon compared to the current situation. Other than intelligent control tools for safe navigation (Chen et al., 2018), the success of the vessel train requires optimal scheduling for autonomous vessel marshaling from the operational planning perspective. Yang et al. (2023) develop a MIP model to decide when and where to join and leave the vessel train for 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.

4.2.2. Port collaboration and terminal coalitions

In the context of horizontal collaboration in maritime transportation, 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 incorporate the cooperation of terminals within a port as terminal coalitions. Ports perform as the hub of maritime shipping, and one of their major tasks is to provide (un)loading services for the calling vessels. In port collaboration and terminal coalitions, different ports (terminals) can work together to provide the service, potentially sharing the information of the calling vessels and facilities to use port resources fully (Kavirathna et al., 2020). In this part, we focus on the optimization models that support using shared resources through port collaboration or terminal coalitions.

Berths sharing. For the port operators, port capacity can not be moved physically from one port to another due to geographical restrictions. Thus, the studies focus on sharing the service requirements of the calling vessels. 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. Venturini et al. (2017) propose a multi-port BAP allowing vessels to change the calling sequence of the port, which indicates the port coalition among ports along the predefined route. The authors use CPLEX to solve small-scale instances. Then, a discrete and a continuous berthing layout of BAP are explored in Martin-Iradi et al. (2022) and Martin-Iradi et al. (2024), respectively; they develop an exact method based on the branch-and-price algorithm for large-scale discrete BAP and an adaptive large neighborhood search (ALNS) heuristic for a continuous setting. Besides, Dong et al. (2023) propose another concerning decision on the capacity-sharing rate for collaboration-involved ports. They formulate a three-stage model consisting of two collaborative ports, providing decisions on port capacity-sharing rate and the terminal handling charge to maximize the social welfare of the port coalitions.

Other resources sharing. Many papers focus on other shared resource allocation, such as internal trucks and yard space. Imai et al. (2008) first propose a BAP model allowing vessels to transfer to another terminal to minimize the total service time. Cho et al. (2021) consider a berth allocation and quay crane assignment problem (BACAP) 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. Lyu et al. (2022) further incorporate the transshipment operations between feeder vessels and mother vessels when implementing vessel reassignment in BACAP within the concept of terminal collaboration. Budipriyanto et al. (2015) formulate a conceptual BAP model under uncertainty using the collaborative approach. Lalla-Ruiz et al. (2015) propose a decentralized cooperative method for BAP by grouping individual carriers and sharing information among group partners. Ma et al. (2020) conduct numerical experiments for resource-sharing strategies among five terminals of Hong Kong Port. They evaluate 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. He et al. (2013) propose a collaborative internal truck scheduling problem using a simulation optimization method. Yang et al. (2020) develop a multi-objective MIP model for internal truck allocation in ITT based on truck sharing among terminals.

4.2.3. *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 a container drayage operation (Macharis & Bontekoning, 2004). Container drayage operations account for a significant portion of the total cost in maritime container shipping (Cheung et al., 2008). Typically, there are four container drayage requests: inbound full, outbound full, inbound empty, and outbound empty. The independent organization of container pickup and delivery results in many unproductive trips. To address this, studies focus on the collaborative scheduling problem for drayage operations.

Collaborative truck scheduling. Although collaboration is not always explicitly stated, many studies optimize truck scheduling by pooling or clustering container drayage requests. For example, Zhang et al. (2010) model multi-depot drayage operations as a multi-TSP with time windows, aiming to minimize total transport time. Various heuristic and exact methods are developed to improve solution quality and efficiency, including deterministic annealing (Braekers et al., 2013), branch-and-price (Fazi et al., 2023), and tabu/local search approaches (Xue et al., 2015, 2014). Some works extend the models to incorporate empty container sharing (Sterzik et al., 2015), tractor-trailer coordination (Shiri & Huynh, 2018), and backhaul clustering (Lai et al., 2013). Collaborative strategies such as internal truck sharing and capacity pooling are shown to reduce empty trips, costs, and emissions (Schulte et al., 2017).

Truck platooning. Truck platooning has recently gained heightened interest (Bhoopalam et al., 2018), which 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 improve the productivity of container drayage operations. Xue et al. (2021) propose a generic MIP model for a new truck platooning mode aimed at container drayage, in which multiple trucks in a platoon use one driver, and the empty containers are shared among different customers. You et al. (2020) further incorporate the interaction and coordination between different platoons. To make the platoon mode more flexible, Yan et al. (2023) enhance 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. Peng and Xue (2023) distinguish the fuel consumption based on the laden-or-empty state of trucks to further optimize the truck platooning schedule for enhanced costs and emissions reduction. Pourmohammad-Zia et al. (2023) propose a new approach by applying AGV platoons to fulfill container drayage requests. The authors consider the number of available AGVs as uncertain in their proposed bi-objective MIP model to reflect a more practical setting.

4.3. *Shared costs or 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 of the potential co-optetive relationship mainly existing in horizontal collaboration, most relevant studies are aimed at horizontal collaboration rather than vertical collaboration (Deng et al., 2022). In general, fairness, stability, and uniqueness are three important properties that we measure in the payoff allocation methods. In Table 5, we categorize the studies by the approaches they apply to allocate payoffs. We also report the properties of the allocation method and indicate whether it is centralized or decentralized. Although there are no substantial studies exclusively aimed at maritime shipping, some theoretical methods appear inspiring for collaborative maritime and port transportation, and thus we also include these studies.

4.3.1. *Cooperative game theory*

Pay-off allocation methods based on cooperative game theory can present better properties than simple proportional allocation (Verdonck et al., 2016). In cooperative game theory, the Shapely value, core, nucleolus, and further derivative methods based on these concepts are widely applied to horizontal collaboration stability and fairness problems (Guajardo & Rönnqvist, 2016). In this part, we mainly focus on the payoff allocation problem appearing in horizontal collaboration and discuss their approaches based on cooperative game theory.

The directly relevant studies on maritime and port transportation are limited. Wen et al. (2019) focus on a centralized collaborative form of the shipping pool in the tramp shipping market, where a fleet of ships owned by different stakeholders is pooled together to be operated cooperatively. They study the maximization of the pool profit and the fairness of profit sharing by comparing different methods defined in cooperative game theory. Giudici et al. (2021) derive an innovative cost allocation method based on a bargaining outcome for hinterland container transport cooperation, and they prove that the proposed approach is equivalent to the Shapley value. Moreover, the authors examine the stability of such collaboration by analyzing the sensitivity of the membership of the proposed cost allocation to the core by deriving a parametric cooperative game. Bouchery et al. (2022) apply the core and the Shapley value to allocate the platooning costs to the individual truck company innovatively by proposing an approximation game, and they testify their payoff allocation methods based on the setting of the Port of Rotterdam. Martin-Iradi et al. (2022) design a collaborative berth allocation game, applying Shapley value to distribute the cost savings from a potential collaboration between the shipping line and terminal operators.

Table 5
Payoff allocation in collaborative transportation.

Method	Type		Property			Area		Reference
	C	D	F	S	U	G	M	
Shapley Value	✓		✓		✓	✓		Krajewska et al. (2008), Vanovermeire and Sörensen (2014a)
	✓		✓		✓		✓	Martin-Iradi et al. (2022)
Core	✓			✓		✓		Guajardo and Rönnqvist (2015), Öner and Kuyzu (2021)
	✓			✓			✓	Lyu et al. (2025)
Nucleolus	✓			✓	✓	✓		Guajardo and Jörnsten (2015)
	✓			✓	✓		✓	Lyu et al. (2025)
Derived method	✓		✓	✓		✓		An and Chen (2022), Vanovermeire and Sörensen (2014b)
							✓	Bouchery et al. (2022), Giudici et al. (2021)
Comparison	✓		✓	✓	✓	✓		Frisk et al. (2010), Lozano et al. (2013)
	✓		✓	✓	✓		✓	Wen et al. (2019)

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

Lyu et al. (2025) develop a row generation algorithm to obtain the core and the nucleolus solution of cost allocation based on cooperative game theory for a collaborative berth allocation problem.

Much more work is found within a broad concept of transportation while inspiring a lot for promoting collaboration in maritime freight transportation, and we briefly conclude them as follows:

Shapley value. Krajewska et al. (2008) apply the Shapley value Method to allocate the costs among the collaborative freight carriers. There are also similar applications in other collaborative planning problems, such as hub location (Habibi et al., 2018) and inventory routing (Olgun & Aydemir, 2021).

The core. The core condition ensures no sub-coalition provides better incentives for partners to leave, thereby maintaining coalition stability. Guajardo and Rönnqvist (2015) and Guajardo et al. (2018) present a collaborative planning model for coalition structure and cost allocation, incorporating the core condition to ensure stable collaboration. Tinoco et al. (2017) examine the impact of cost allocation or profit-sharing on collaboration stability in inventory management. Öner and Kuyzu (2021) develop an MIP model to identify stable coalitions and cost allocations for truckload shipment bundling. Other applications include integrated facility location and vehicle routing (Osicka et al., 2020), and collaborative truckload for perishable products (Li et al., 2016).

The nucleolus. The nucleolus, introduced by Schmeidler (1969), 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. The nucleolus is computationally challenging; thus, its application in collaborative transportation models is limited, and only several studies can be found in the literature (Guajardo & Jörnsten, 2015).

Innovative approaches. An and Chen (2022) introduce a new class of games called double-type player games and propose a new method to generate a semi-core cost allocation called the proportional cross-evaluation method. Vanovermeire and Sörensen (2014b) and Vanovermeire et al. (2014) propose that flexible delivery time contributes to a decrease in the total cost of the coalition. Thus, the flexibility of partners should be considered in cost allocations to encourage it. Aimed at airline transport, Yea et al. (2022) develop a new allocation scheme based on cooperative game theory, named min-variance solution to deploy the joint profits by minimizing individual partners' intent to form sub-groups, thus ensuring the alliance's stability.

Some papers compare the above-introduced costs or profits allocation methods. Frisk et al. (2010) and Lozano et al. (2013) investigate several sharing mechanisms, including the Shapley value, the nucleolus, separable and non-separable costs, shadow prices, and volume weights examined in a forestry logistics industry.

4.3.2. Non-cooperative game theory

While cooperative game theory provides powerful tools for ex-post allocation, a complementary stream of literature employs non-cooperative game theory to design mechanisms that incentivize cooperation ex-ante. This approach is particularly relevant in contexts where stakeholders are independent entities with conflicting interests, and collaboration must be induced through carefully designed contracts or incentives rather than assumed. For instance, in empty container repositioning, as discussed in Section 3, Xie et al. (2017) exemplify this approach by designing a buy-back contract between shipping lines and freight operators. Their model frames the interaction as a non-cooperative game, demonstrating how such a contract can align individual incentives with system-wide goals, reducing inefficiencies and creating Pareto-improving outcomes. This work underscores that the allocation rules derived from cooperative games often represent the outcome of a non-cooperative bargaining process or must be implemented through non-cooperatively robust mechanisms. Therefore, both perspectives are essential for a complete understanding of achieving and sustaining collaboration in shared-resource environments.

Building on non-cooperative game theory, many researchers focus on the mechanism design of the cost allocation or profit sharing problem, accompanying horizontal collaboration problems. Zhang et al. (2018) design a Moulin mechanism for the cost allocation in a freight consolidation system with one consolidation center and a common destination, considering the features defined in game theory: budget-balance guarantee, economic efficiency, and truthfulness. Chu et al. (2020) focus on the cost allocation mechanism design to ensure that the partners have no motivation to take hidden actions to influence the coalitional benefits. Zou et al. (2021) propose a hybrid proportional online cost-sharing (HPOCS) mechanism to tackle the cost allocation problem in horizontal supply chain collaboration. Zhang et al. (2022a) design an acyclic mechanism based on bin-packing solutions for freight consolidation problems, which also provides strong Nash equilibria from the perspective of non-cooperative game theory. Gansterer et al. (2020) design an auction-based method allowing individual logistics partners to exchange transportation requests under incomplete information. For each bid, an NP-hard routing problem has to be solved. Los et al. (2020) explore the value of different information types in auction-based collaborative freight transport problems.

4.4. Critical evaluation of the modeling and solution methods in horizontal collaboration

The modeling and solution methods for horizontal collaboration in maritime logistics exhibit a diverse range of approaches tailored to different problem settings.

The majority of the optimization models rely on MIP, often enhanced with heuristics for approximation or exact algorithms to improve computational efficiency. Some studies also incorporate multi-objective programming (Chen et al., 2022a), metaheuristics (e.g., genetic algorithm (Wong et al., 2022), tabu search (Sterzik et al., 2015)). Recently, machine learning-based methods (Munim et al., 2020) emerged to solve stochastic, complex, and large-scale problems. In vessel slot allocation (VSA) and truck scheduling (TS), heuristic and decomposition-based methods (Fazi et al., 2023) are commonly applied to handle the high computational complexity associated with multi-party collaboration. Robustness considerations. Robust optimization (RO) and constraint-based approaches (Pourmohammad-Zia et al., 2023), are also observed in recent studies.

Key challenges in horizontal collaboration are the balance of cost efficiency (Vanovermeire & Sörensen, 2014b), profit-sharing fairness (Lyu et al., 2025), and practical constraints such as recovery from disruption and decentralized decision-making (Lyu et al., 2022). In VSA problems, different levels of slot-sharing strategies impact cost savings and profitability (Parthibaraj et al., 2018) . BAP in terminal collaboration requires a careful vessel reassignment strategy to minimize congestion (Budipriyanto et al., 2015). Truck scheduling (TS) and platooning scheduling (PS) focus on synchronization and cost-sharing among multiple carriers (Phan & Kim, 2016), often integrating sustainability objectives like emissions reduction.

In collaborative transportation, fair and stable payoff allocation remains a significant concern. The Shapley value, core, and nucleolus methods are widely applied to ensure equitable cost distribution among participants (Lyu et al., 2025; Martin-Iradi et al., 2022). The Shapley value emphasizes fairness, whereas the core and nucleolus approaches prioritize stability and uniqueness in coalition formation (Guajardo & Rönnqvist, 2015). Hybrid and derived payoff allocation methods (Giudici et al., 2021) further refine fairness measures, particularly in complex and multi-agent maritime collaborations.

Despite advancements, several limitations exist. Many optimization models remain computationally intensive, requiring problem-specific heuristics for practical implementation. Decentralized collaboration models are underdeveloped, limiting applicability in real-world multi-stakeholder environments. Future research should explore data-driven approaches, reinforcement learning-based decision-making, and blockchain-enabled trust mechanisms to enhance coordination and efficiency in horizontal collaboration.

Consequently, horizontal collaboration in maritime logistics includes a mix of mathematical optimization, heuristic algorithms, and cooperative game theory to improve efficiency and cost-sharing. However, scalability, real-time adaptability, and equitable payoff distribution remain key challenges that need further exploration.

5. Overview of the research domains, modeling approaches and solution methods

To provide a cohesive bigger picture for the reader, we illustrate the proposed multi-dimensional analytical framework in Fig. 6. The foundational element of our framework is the direction of collaboration, which serves as the primary organizing principle for the entire paper. Within each of two primary collaborative directions (vertical and horizontal), we analyze collaborations through three consistent core dimensions: (i) stakeholders (Who): this dimension identifies the key actors involved in the collaborative effort, clarifying their roles and interrelationships. (ii) objectives (Why): this dimension examines the primary drivers and anticipated benefits, which we categorize into the triad of Efficiency, Decarbonization, and Resilience. (iii) arrangements (How): this dimension classifies the operational depth of collaboration, ranging from basic information exchange to more advanced integrated operations and joint planning. thereby allowing the reader to discern the bigger picture and the interconnections between different research streams.

Next, we outline the dominant modeling and solution methods used to address complex decision-making and optimization problems within the scope of collaborative maritime and port operations. Each subsection describes a specific methodological approach, its association with particular problem types, and its strengths and limitations. Finally, we provide a critical evaluation of these methods and their integration.

Optimization techniques. Optimization techniques play a crucial role in enhancing decision-making processes within collaborative settings (Cleophas et al., 2019). These methods provide structured frameworks to optimize resource allocation, scheduling, and cost efficiency while balancing constraints such as time, environmental impact, and stakeholder objectives.

In hierarchical supply chains and maritime operations for vertical collaboration, optimization methods are widely applied to problems such as BAP, TVS, and VSP. MIP and MINLP are frequently used to model these challenges, offering precise and structured solutions. However, due to the complexity of large-scale maritime systems, heuristic and metaheuristic techniques, such as GA and ALNS (Zhang et al., 2022c), are often applied to enhance computational efficiency. In decentralized logistics and multi-entity partnerships for horizontal collaboration, optimization techniques help coordinate VSA, TC, and CDC. These problems often require multi-objectives to balance multiple stakeholders' interests and RO (Pourmohammad-Zia et al., 2023) methods to manage uncertainty. Additionally, decomposition-based (Fazi et al., 2023) approaches improve computational feasibility when handling large collaborative networks. While optimization techniques offer significant improvements in operational efficiency, they face scalability limitations in large-scale and dynamic environments. Exact methods provide optimal solutions but may be computationally prohibitive, whereas heuristics trade optimality for efficiency.

Game theory. Game theory is widely applied in collaborative logistics to model interactions between stakeholders with competing or cooperative objectives (Guajardo & Rönnqvist, 2016). It provides structured mechanisms for decision-making in cost-sharing, resource allocation, and coalition formation.

In vertical collaboration, cooperative game theory (Martin-Iradi et al., 2022; Vanovermeire et al., 2014) is used to optimize decision-making among port operators, shipping lines, and logistics providers. Methods such as Shapley value and nucleolus are applied to ensure fair and stable cost distribution among collaborative partners. In horizontal collaboration, involving multiple independent entities requires game-theoretic models (Lyu et al., 2025) to ensure equitable profit-sharing and coalition stability. The Shapley value, core, and other fairness-focused methods help manage vessel slot-sharing, truck platooning, and multi-carrier logistics coordination. Despite its usefulness, game theory is computationally demanding, particularly for large-scale multi-agent systems.

Agent-based modeling. Agent-based modeling provides a framework for investigating interactions between independent decision-makers in complex environments (Baindur & Viegas, 2011; Vaněk et al., 2013). In vertical collaboration, agent-based modeling is used to simulate supplier-buyer interactions, allowing analysis of policy changes, congestion management, and logistics network dynamics. For decentralized logistics in horizontal collaboration, agent-based modeling is used to study emergent behaviors in multi-actor environments, such as shipping alliances and freight pooling systems. While agent-based modeling captures emergent phenomena and behavioral dynamics, it often lacks scalability.

Federated machine learning . Federated machine learning offers a data-driven approach for predictive modeling and decentralized learning, enabling enhanced decision-making in collaborative logistics (Giannopoulos et al., 2024).

In vertically structured logistics, federated learning techniques enhance predictive maintenance, demand forecasting, and risk assessment, improving operational efficiency. In horizontal collaboration, federated

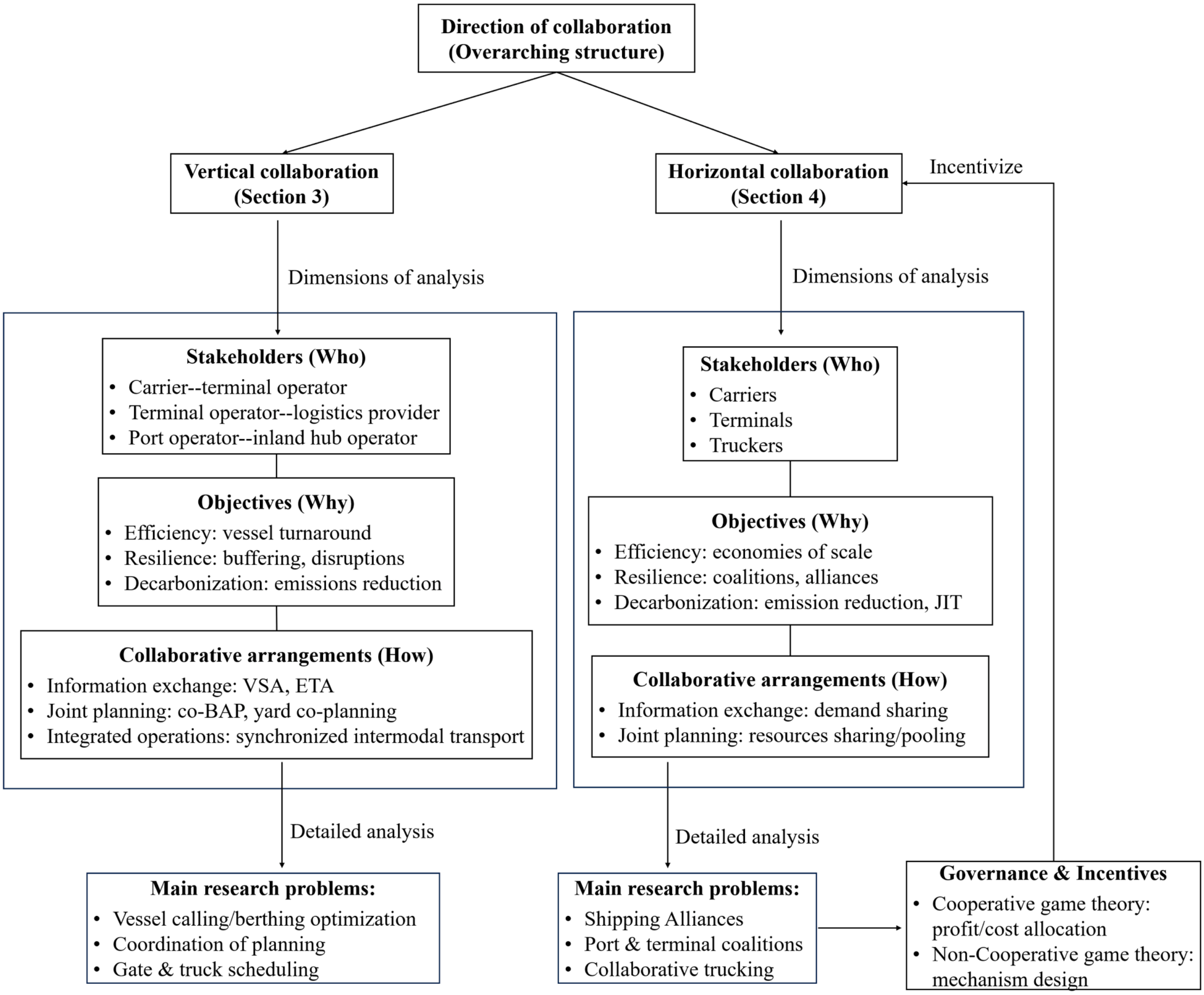

Fig. 6. The multi-dimensional analytical framework for collaborative maritime and port operations.

learning allows multiple stakeholders to share insights while preserving data privacy, and enhancing vessel scheduling, demand prediction, and fleet coordination. Despite its potential, federated learning faces challenges such as data heterogeneity, privacy concerns, and suboptimal solutions due to limited information exchange.

Summary. Each of the reviewed methodologies excels in addressing specific problem types but also presents inherent limitations. Combining them provides a more robust framework for tackling real-world complexities. For instance, integrating game theory with agent-based models captures both strategic decision-making and emergent behavior. Hybridizing machine learning with optimization techniques enhances decision-making under uncertainty, and federated learning can augment game-theoretic and agent-based models to facilitate decentralized decision-making.

Vertical and horizontal collaboration strategies need more advanced methods to improve coordination, information sharing, and overall system performance. The future of complex problem-solving lies in the synergy of these methodologies. Developing unified frameworks that leverage their complementary strengths will enable more effective solutions to dynamic, multi-agent, and large-scale optimization challenges.

6. Practical implementations and collaborative platforms in real world

Regarding the collaboration in maritime and port transportation, there are increasing numbers of platform-based implementations in business practices. Transportation platforms are on the rise (Standing et al., 2019), with successful examples such as Uber. In the platform-based collaboration setting, the platform acts as the intermediary between shippers and carriers. It generates collaborative plans and steers the collaboration, providing both parties with information. In contrast to conventional transportation companies, platform providers mostly do not have immediate control over the physical resources to move goods (Atasoy et al., 2020). In the maritime sector, multiple similar platforms have emerged, targeting slightly different problems and application areas. Table 6 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 (Moros-Daza et al., 2020), which enables improved coordination of vessel arrivals and port operations, such as *Portbase* and

Table 6
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 and 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: prototype; C: concept

OnePort. Moros-Daza et al. (2020) review the development of PCSs from 2001 until 2019 and detail the different PSC platforms, their functions, and benefits for stakeholders. Aydogdu and Aksoy (2015) investigate the quantitative benefits of PSC implementation by Turkish port by simulation method, and Tsamboulas et al. (2012) propose an evaluation framework for PCSs. To reduce GHG emissions, the company NAPA provides the Blue Visby platform to approach "Just-in-Time" by eradicating the bottleneck of "sail fast, then wait."

In recent years, several new phenomena with IoT and blockchain technology applications have emerged. Irannezhad et al. (2018) integrate IoT and blockchain with PCSs to address the bill of lading issues, and Caldeirinha et al. (2022) unveil the trends from PCS towards Physical Internet (PI), such as the *NxtPort* data usage platform in Port of Antwerp, *NextLogic* introduced by the Port of Rotterdam, and *Nexus* approved by the Port Administration of Sines. Specifically, Pagano et al. (2022) introduce the *C-port* prototype in Port of Livorno, and Kapkaeva et al. (2021) focus on the digital platform *SmartPORT* at Port of Hamburg.

A number of innovative platforms based on the sharing economy or reuse concept can be found in the liner shipping market. *CargoStream*, a centralized collaboration platform for the port supply chain, is developed for transport service organizers 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, providing good examples for reducing transport costs, emissions, and port congestion. 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, online platforms, such as *Xchange* and *iContainers*, carry out container exchanges to improve collaboration and simplify the global container trade. We could also find port-associated truck haulage platforms, such as *E-shipping Gateway* and *Landstar*. These truck-haulage service platforms attempt to take over the managerial functionality of truck companies by offering information on haulage demand directly to truck drivers via smartphone applications. A significant advantage is that the port is willing to share information regarding to-be-loaded containers with the platforms as a triple-win game for port operators, platforms, and truck companies.

However, as shown in Table 6, 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.

7. Research agenda: Bridging practical challenges and theoretical research

Collaboration has the potential to achieve a high level of efficient, decarbonized, and resilient maritime and port transportation. In this work, we outline various collaboration types, from academic research to practical implementation. The practical implementations summarized in Table 5 highlight several persistent open issues that warrant further academic investigation. Although many OR papers have contributed to the challenges in planning encountered by different forms of collaboration, approaches to deal with more efficient, advanced, and flexible collaborative maritime shipping still need to be addressed. The future research agenda is listed as follows to reap the benefits of collaborative strategies efficiently.

- ***Port as information centers****: How to design data-sharing architectures that balance transparency with confidentiality, and how to incentivize participation in port community systems?*

  The importance of data sharing seems to be increasingly recognized in the maritime shipping industry and it establishes new types of platform-based collaboration. Digitalization initiatives and data sharing are being pursued and an increasing number of ports are engaged in the synchronization, and optimization associated with port call operations through initiatives. In these cases, platforms need to develop models that allow limited information sharing and enable effective collaboration under these conditions (Los et al., 2020).

  Collaboration incentives are essential to decision-support models for collaborative planning. Significantly, these models need to be developed at an operational planning level and applied dynamically (Lyu et al., 2025). The relevant research directions can cover carefully designed payoff-sharing mechanisms, different information-sharing options, and multiple degrees of centralization in decision-making. Game theory has been demonstrated to be effective for many collaborative freight transportation problems, while the application dedicated to the maritime domain is very limited. Additionally, concerning implementation, the potential for fraud by stakeholders in co-opetition also needs to be considered according to the different use cases.
- ***Bundling and synchronizing flows****: How to optimize the consolidation of freight flows across multiple operators while simultaneously accounting for uncertainty and flexibility?*

  New features of pooling demands within the collaborative systems require new models for conventional problems, such as stowage planning (Korach et al., 2020) and yard container stacking (Boschma et al., 2023) within the shipping alliance, integration of port operation and ocean shipping service (Tan et al., 2018), empty container transportation in a collaborative network (Vojdani et al., 2013) and first & last-mile container port drayage operation(Chen et al., 2022b). Real-time planning relating to disruptive considerations is interesting. The disruptions of container flows caused by the COVID-19 pandemic, Notteboom et al. (2021) bring 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 (Wen et al., 2019) in a highly dynamic environment. Moreover, 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 (Zheng et al., 2022).

- ***Modelling multi-modal collaboration:*** *How to model and optimize collaborative operations that span multiple transport modes and jurisdictions?*

  Operations involving multiple transport modes (e.g., integrated sea-land corridors) and crossing different jurisdictions inherently involve numerous stakeholders and complex interactions. This setting intensifies the challenges of collaborative planning. Future models should move beyond simplified assumptions (e.g., homogeneous fleets, fixed schedules, deterministic conditions) to incorporate realistic constraints such as heterogeneous assets, dynamic environmental factors (tides, drafts), port physical layouts, and soft operational restrictions (Agarwal & Ergun, 2008, 2010; Armas et al., 2018; Corry & Bierwirth, 2019; Lalla-Ruiz et al., 2016; Zhen et al., 2017). Addressing these complexities requires advanced optimization techniques. Given the NP-hard nature of many such problems, heuristic methods remain vital, but there is growing potential in integrating Machine Learning (ML) with Operations Research (OR). This hybrid approach can leverage ML's learning capabilities for pattern recognition and prediction, while retaining OR's strengths in mathematical rigor and explainable optimization (Bengio et al., 2021; Filom et al., 2022).
- ***Environmental issues vs. cost-based concerns:*** *How to align economic and environmental objectives in collaborative planning, especially in empty container repositioning and green corridor development?*

  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 emission (Alzahrani et al., 2021). The green corridors based on applying green fuels (e.g., liquid natural gas, hydrogen, ammonia, and so on) are conceptually established on several shipping routes, which involve multiple collaborations. The studies that can provide operational support, such as network design (Ursavas et al., 2020) and refueling optimization (Kuby et al., 2009), are very limited.
- ***New technologies application:*** *How to integrate IoT, blockchain, and AI into collaborative platforms to enhance trust, automation, and decision-making?*

  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 (Bhoopalam et al., 2018). 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 (Shouwen et al., 2021).

  Furthermore, the advent of shared fleets of automated vehicles or autonomous vessels for port-centric transport (e.g., between terminals or to inland hubs) introduces a new layer of collaborative complexity. These assets are likely to serve multiple logistics service providers, making their management a natural collaborative setting. Key research questions include the design of fair and dynamic allocation mechanisms, the development of real-time coordination algorithms for heterogeneous fleets, and the integration of such systems within broader port community platforms. This area lies at the intersection of collaborative logistics, intelligent transportation systems, and multi-agent optimization, offering rich opportunities for novel OR and AI methodologies.

Practical developments alike demonstrate that larger-scale maritime collaboration becomes feasible. This contributes to the ambition of interconnecting heterogeneous network services and transport resources to an efficient transportation network, also referred to as the Physical Internet. With approximately 90% of world trade going over the sea, the different methods of planning (e.g., scheduling, routing, and allocating) this huge network will become crucially important for the global economy. For operations research, this poses significant opportunities and challenges at the same time. This kind of large-scale collaboration could significantly increase resource utilization, general efficiency, and thus, the sustainability of the maritime sector (and the global economy). On the other hand, new models need to be scaled up to previously unknown dimensions, and federated and distributed methods are needed for secure and robust operations. This will require further integration of classic optimization techniques with (federated) machine learning and agent-based modeling.

8. Conclusion

While collaboration has a long tradition of generating competitive advantages in the maritime industry, with the pressure of increasing volume and sustainability objectives, new Operations Research (OR) approaches are needed to enhance efficiency, decarbonization, and resilience.

In this work, we review the collaborative OR methods in maritime and port transportation studies and showcase the relevant implementations in the real world. We present a comprehensive examination of prior research and practical applications concerning collaboration within the maritime sector, taking a critical look at the challenges these collaborative transportation systems face and how OR methodologies contribute to solutions. We identify two key collaboration types (i.e., vertical and horizontal collaboration) consisting of three main stakeholders (i.e., shipping lines, port or terminal operators, and other logistics service providers), analyzing the related collaborative systems and strengthening the OR contributions (e.g., innovative models, algorithms, and mechanisms). In this way, we connect fragmented problems and solution approaches to provide a systematic view of maritime collaboration techniques for researchers and practitioners in OR.

Prior research has shown that collaborative freight systems supported by OR techniques have significant potential to achieve higher efficiency, decarbonization, and resilience in maritime and port transportation. These collaborative systems inherently open up new spaces for decision-making optimization while simultaneously introducing novel OR challenges, thereby calling for the development of innovative models to support system functionality. We elaborate on the significance of accounting for uncertainty and adaptability within collaborative planning models and algorithms. Additionally, we highlight the potential of automated technology to stimulate innovative collaborative approaches. 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. This area requires further research, mainly through combining game theory, agent-based modeling, and federated machine learning methodologies with prevailing optimization techniques. With a view on recent developments in the sector, we emphasize that the establishment of green maritime corridors requires new collaborative models considering the distinct stakeholders and creating strong incentives to facilitate the decarbonization process toward achieving net-zero emissions within maritime transportation. We outline all these points in the research agenda for future investigations.

In this way, this literature review deepens the understanding of collaborative concepts for maritime researchers and practitioners, highlighting future OR research directions such as hybridized methods and federated collaboration approaches for extended real-world implementations in collaborative maritime systems.

CRediT authorship contribution statement

Xiaohuan Lyu: Writing – review & editing, Writing – original draft, Formal analysis, Methodology, Conceptualization; **Kevin Tierney:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization; **Frederik Schulte:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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