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Collaborative Berth Allocation with Row Generation Methods for the Core and Nucleolus

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Motivation Advances in information-sharing technology have stimulated innovative ways to deal with the increasing demands in the domain of logistics and transportation. Among them, collaborative planning strategies, where individual stakeholders can provide service cooperatively based on resource (e.g., infrastructure and information) sharing, are widely accepted as a promising approach to numerous decision-making problems. Employing these strategies, economic, environmental and many other intangible benefits can be obtained (Cleophas et al. 2019).

Accounting for over 90% of global trade, the maritime shipping industry faces great opportunities as well as challenges related to collaboration. Over the past two decades, compound annual growth in maritime trade has been 2.9 percent (UNCTAD 2021). The increasing rate urges the terminals to expand their capacity, not only to ensure the efficiency of port services but also to enhance port resilience when facing enormous disruptions, for instance, the breakdown of the COVID-19 pandemic. Thus, improving the efficiency of port resource utilization via effective collaboration among multiple stakeholders (e.g., shipping companies and terminal managers) has received much attention in recent years.

Problem Statement Berth planning is a critical decision process by terminal managers when it comes to efficient port operation as well as smooth maritime transport. From an Operations Research perspective, it has been modeled mathematically as Berth Allocation Problem (BAP) to decide when and where to discharge (or load) the incoming vessels.

Bierwirth and Meisel (2010) classify the models and algorithms that have been developed in BAP, but the collaborative BAP requires different considerations. First, collaborative planning is more complex as it deals with the coordination of multiple parties, and thus, it requires new models to support collaboration at the operational level. Second, in the context, all stakeholders are more concerned with individual interests and may be reluctant to share their resources if they cannot obtain more benefits. In this regard, successful implementations require planning models that consider not only resource allocation but also the incentives for individuals to form coalitions in order to steer effective collaboration in practice (Schulte et al. 2019). Therefore, another significant concern is how to incentivize the individual stakeholder to collaborate and abide by the coalitional regulation.

Approach In this paper, we extend the work of Lyu et al. (2022) to study the Collaborative Berth Allocation Problem (CBAP) in which all terminals within one port serve the calling vessels cooperatively, and add to related work on collaborative berth allocation by Martin-Iradi, Pacino, and Ropke (2022). To this end, we make the following main contributions.

First, we present a mathematical model to minimize the cost of discharging (or loading) operations for the terminal operators and the turnaround time for the calling vessels. Figures 1 and 2 illustrate the berthing plan with and without the terminal collaboration based on an example port with three terminals. In Figure 1, terminal managers make their own decisions on berth allocation independently, that is, the calling vessel's berth planning is limited by the internally accessible berth and quay crane resources. While in the collaborative case shown in Figure 2, the calling vessel can be arranged at another terminal of the coalition where a better service time window is provided. The extended CBAP model achieves a simultaneous berthing plan for multiple terminals within a port.

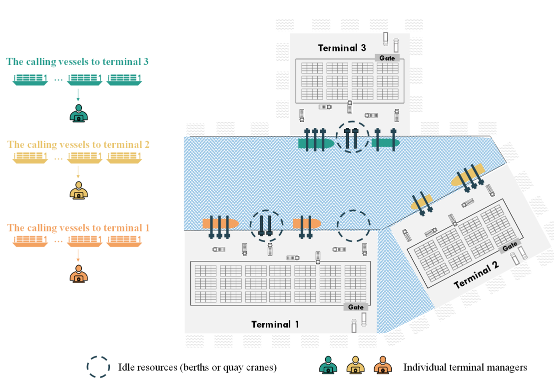

Figure 1 Without the terminal collaboration

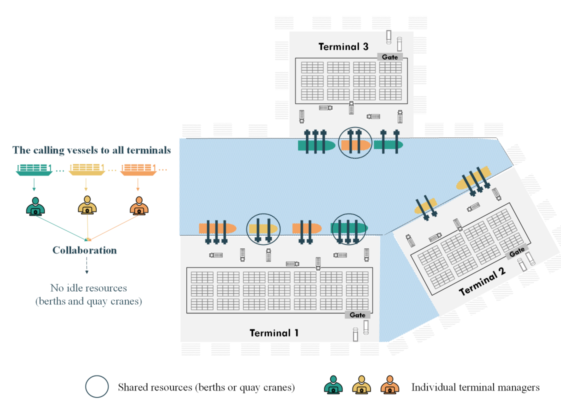

Figure 2 Within the terminal collaboration

Second, we develop a row-generation-based algorithm to calculate the core solution for distributing the joint cost. Depending on the settings of the problem instances, it is possible that no allocation can reach the core condition. In such situations, the devised row-generation algorithm can provide lower bounds, defined as the cost savings for individual terminal operators so that joining the coalition is attractive.

For individual members, a natural concern is maximizing their benefits. The core solution can guarantee the stability of the coalition, however, it is often not unique. Thus, the question remains: which one is the best? The nucleolus is considered the "most stable" solution in the sense that it lexicographically minimizes dissatisfaction among all coalitions. The nucleolus was explored by Guajardo and Jörnsten (2015) as a solution concept connected with the optimization problem with attractive properties: it is unique and it lies in the core (if the core is not empty). Thus, third, we further develop the algorithm to verify and find the nucleolus solution to distribute the joint costs among collaborative terminal operators. The simplified representation of the solution framework is shown in Figure 3. We improve the Kohlberg Algorithm introduced by Kohlberg (1971) such that the iteration times can be reduced to n from $2^n - 1$ (with n as the number of players). Then, we propose a decent-based constructive algorithm combined with the CBAP model to find a solution to be verified until we find the nucleolus.

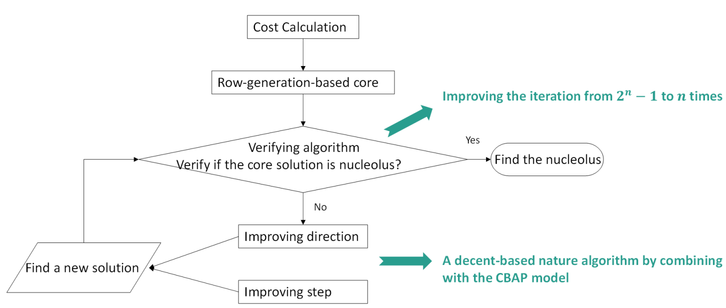

Figure 3 **Simplified representation of the framework of verifying and finding nucleolus mechanism.**

Results and Conclusions Preliminary results of our experiments demonstrate that the collaborative approach for berth allocation can yield cost savings of up to 40%, and show, at the same time, the great potential of alliances among terminals. For instance, at a setting of 5 terminals within a port, Figure 4 shows the different costs of each terminal under different cost allocation methods, and Figure 5 shows the ratio of the cost allocated to each terminal to the total cost. The core solution obtained by the proposed row-generation algorithm can satisfy the coalitional rationality requirements. Moreover, the designed mechanism derives nucleolus solutions such that each member realizes clear cost savings relative to the row-generation solutions, in all conducted experiments.

Although the concept of CBAP has been recognized over the last decade, the matching planning models are still in their infancy. This work contributes to making the collaborative strategy

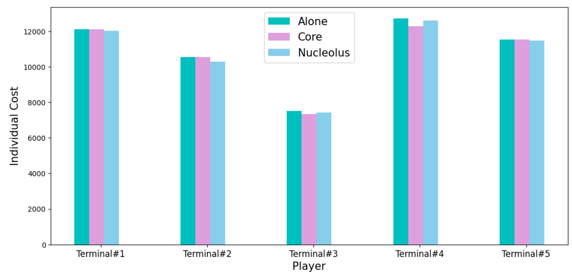

Figure 4 Individual cost for each terminal

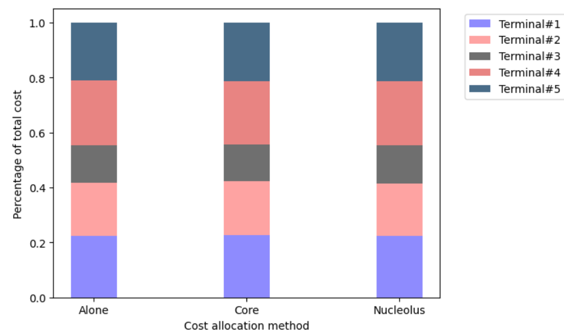

Figure 5 Cost percentage of each terminal

play a role in practice. In particular, our berth planning model provides decision support for the mode of horizontal collaboration among terminals. The proposed row-generation-based core gives reasonable distribution methods for the joint cost, maintaining the stability of the collaboration. The mechanism of verifying and finding the nucleolus provides a unique optimal cost allocation strategy, which minimizes dissatisfaction among all coalitions. As far as we know, the developed decent-based algorithm for finding the nucleolus is an innovative exploration to combine with the optimization model. In summary, the CBAP model and cost allocation methods (the core and the nucleolus) based on Cooperative Game Theory proposed in this work not only show the great potential of collaborative strategies but also provide maritime practitioners with strong decision-making support to implement collaboration in practice.

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