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Optimization of Pricing for Priority Use of Port Berths

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ABSTRACT

With the growth of container shipping demand and the increasing size of vessels, the scarcity of frontline port resources, such as berths and quay cranes, has become increasingly prominent. Traditional port operations usually treat berth allocation, quay crane assignment and charging mechanisms as separate decisions, making it difficult to fully reflect the internal relationship among resource scarcity, differentiated service demand and port revenue management. As a differentiated service with service commitment attributes, berth priority usage rights can guide vessels' choices through pricing mechanisms and provide a new approach for optimizing port resource allocation and improving revenue. Therefore, this thesis studies the pricing problem of berth priority usage rights, focusing on the coordinated optimization relationship among priority pricing, berth planning and quay crane allocation. This thesis first defines the service connotation of berth priority usage rights, regarding them as differentiated services in which the port provides vessels with earlier latest service completion commitments. On the demand side, reservation price and consumer utility theory are introduced to describe vessels' willingness to pay for different priority levels. Vessels make choices according to the net utility formed by the difference between the reservation price and the actual price of each level. When positive net utility exists, a vessel chooses the priority level with the highest utility; when all paid priority levels fail to provide positive net utility, the vessel chooses the non-priority option. In this way, the priority price is not only a charging parameter, but also an important decision variable that affects vessels' priority-level choices, demand structure and resource allocation results.

KEYWORDS

Berth Planning; Priority Rights; Modeling.

1. INTRODUCTION

Container terminals are complex in composition, including berths, quay cranes, horizontal transportation facilities, vertical transportation facilities, and other operational equipment. Among them, due to the high construction costs, berths and quay cranes are relatively scarce components at the forefront of the terminal and are also the parts where shipping companies' vessels interface with the terminal's loading and unloading equipment. This study focuses on port berth priority usage pricing, allocating berths and quay cranes to vessels based on the priority usage rights of the berths selected by visiting vessels (referring to container ships). Considering vessel priority usage pricing and demand relationship functions, as well as the loading and unloading workload of container ships, combined with vessel service completion time constraints, the number of berths, and the number of quay cranes, decisions are made on vessel berth priority usage prices, berth allocation, and quay crane allocation. Vessels that purchase berth priority usage rights will advance their service times, with the goal of maximizing port berth priority usage revenue. Such priority usage pricing has both important theoretical and practical significance.

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Theoretical Significance: As a key node in the global supply chain, the operation and management of ports involve the interdisciplinary application of multiple theories. Current research on port resource allocation mainly focuses on berth allocation strategies and throughput optimization, while systematic research on the pricing of berth priority—a special resource that is scarce and exclusive—is relatively insufficient. By studying the pricing of berth priority, pricing theory, queuing theory, and pricing models from microeconomics can be combined with actual port operation scenarios, further improving the theoretical system of port economics and providing new perspectives and a theoretical basis for subsequent research.

Practical Significance: Against the backdrop of rapid global trade growth, port throughput continues to increase, and berth resources are becoming increasingly tight, especially in busy large ports, where the time cost for ships waiting to berth is rising. Through a reasonable berth priority pricing mechanism, limited berth resources can be allocated first to ships that are highly time-sensitive and have a strong willingness to pay, reducing vessel port stay time and increasing berth turnover and utilization rates. At the same time, price signals can guide shipping companies to choose appropriate berthing times and berth types according to their own needs and cost-effectiveness, avoiding excessive concentration and waste of resources, achieving optimized allocation of port resources among different users and time periods, improving overall port operational efficiency, reducing social logistics costs, and enhancing the competitiveness of the port in the regional economy. In addition, a reasonable pricing mechanism can attract more high value-added shipping business and customer groups, optimize the port's business structure, and enhance the port's profitability and sustainable development capability.

2. REVIEW OF RESEARCH IN RELATED FIELDS

Berth planning is a fundamental issue in port operational planning. Its core lies in determining suitable berthing positions and operation time slots for arriving vessels based on their expected arrival times, cargo handling requirements, quay conditions, and port operating rules, thereby reducing waiting and delays and improving berth resource utilization efficiency. Lim[1] was among the first to formally describe the berth planning problem from the perspective of combinatorial optimization, pointing out that the problem simultaneously has both temporal sequencing and spatial allocation attributes. Yang Haidong[2], in his research on port berth system simulation, further noted that berth assignment is not merely a queuing service but a dynamic decision-making process influenced jointly by vessel arrival rhythms, berth occupancy status, and service strategies. Imai et al.[3], in their study of dynamic berth allocation problems, clearly stated that the essence of berth planning is a typical spatiotemporal coupled optimization problem, and considering only time scheduling or only spatial layout is insufficient to characterize its true structure. Nishimura et al.[4], in their research on public berth systems, proposed that the high complexity of berth planning is jointly determined by the precedence relationships among vessels, the substitutability between berths, and the unevenness of operation durations. Related research by Zhen et al.[5] points out that vessel berthing positions directly affect yard space allocation, while the available yard space and container yard layout, in turn, constrain vessel berth assignments; thus, the two are fundamentally nested joint decision-making problems. Compared with the traditional approach of handling berths and yards separately, this work places greater emphasis on the systematic coupling between front-end and back-end port operations. More importantly, the study explicitly considers uncertainties in arrival times and operational demands, indicating that in a stochastic environment, relying solely on deterministic optimal plans often cannot guarantee execution effectiveness. Methodologically, the paper establishes an integrated optimization model under uncertain environments, demonstrating the modeling ideas and solution framework for joint allocation of port resources in complex scenarios. Kim and Moon[6], starting from container terminal operations, point out that berth assignment is a prerequisite for quay crane configuration and cargo handling schedule planning, and therefore, the quality of berth decisions directly affects vessel turnaround times and overall terminal throughput.

With the gradual deepening of research, the berth planning problem has formed a relatively clear classification framework. The most common division is between discrete berth planning and continuous berth planning. Imai et al. [7] pointed out that in a continuous shoreline environment, ships can flexibly determine berthing positions while satisfying length and safety distance constraints, which is closer to the actual situation of large public terminals than pre-allocating fixed berths. Cordeau et al. [8] further explained in system modeling that discrete berth planning is convenient for reflecting existing berth boundaries, berth numbers, and dedicated berth management rules in ports, while continuous berth planning allows more flexibility in shoreline utilization but significantly increases the difficulty of handling non-overlapping constraints. Zhang Yantao [9], in the study of berth scheduling based on genetic algorithms, also indicated that as berth boundaries change from fixed to flexible, the solution space expands rapidly. Monaco and Sammarra [10], from the perspective of model strengthening, pointed out that the reason berth planning has long been a focus of port optimization research lies in its characteristics of strong engineering constraints, tight variable coupling, and high solving difficulty. Zhen et al. [11] incorporated tidal constraints and channel traffic control into the berth planning model, extending the traditional berth allocation problem from a generally static shoreline arrangement to a real scenario affected by both natural conditions and navigation order. Compared with earlier studies that only considered the order of ship berthing, this work places more emphasis on the spatiotemporal coupling of berth decisions, indicating that in tidal ports, berth feasibility depends not only on whether the shoreline is available but also on whether ship entry and exit conditions can be met at specific time periods. Hansen et al., from the perspective of cost optimization, proposed that the objective of berth planning can not only be to minimize waiting time but can also be extended to minimize the total cost considering delays, early departures, and resource utilization losses. Wang Hui, in solving the port berth scheduling problem using the ant colony algorithm, also pointed out that the choice between discrete and continuous berths essentially implies different assumptions about on-site port management methods and scheduling flexibility.

3. MODEL CONSTRUCTION

The continuous deepening of global trade integration and the iterative upgrading of the container shipping industry are driving the enhancement of ports' functions and value as comprehensive logistics hubs. The operational efficiency and revenue levels of specialized container ports have become the core leverage for port competition and industry development. Berths and quay cranes, as the central scarce hardware resources of container ports, have configuration efficiency that directly determines port service capacity, ship operation efficiency, and overall profitability. However, under the contradiction between rigid port resource supply and elastic growth of shipping market demand, traditional resource allocation models can no longer meet market-oriented operational requirements, necessitating the use of market-based pricing methods to achieve precise matching and value extraction of resources.

Prioritized berth usage rights, as an important innovative form of market-based resource allocation in ports, provide a market-oriented solution for ships by offering differentiated latest service completion time commitments, helping them avoid anchorage waiting and shorten operation cycles. At the same time, it opens new pathways for ports to revitalize existing resources and create incremental revenue. In actual operations, the demand for prioritized berth usage rights shows obvious price sensitivity. High-priority usage rights, which offer ports' commitment to earlier service completion times, generally possess higher market value. The rationality of the pricing strategy directly determines the realization of port priority revenue. In addition, the pricing of prioritized berth usage rights is not an independent decision; it is highly coupled with berth allocation and quay crane allocation. This requires that ports, while setting prices, simultaneously complete the exclusive allocation of berths and intensive configuration of quay cranes. Coordination among these three aspects becomes key to maximizing port priority revenue.

Currently, domestic and international ports show common issues in the practical operation of prioritized berth usage rights, such as unscientific pricing mechanisms and a disconnect between resource allocation and pricing decisions. Most ports adopt experience-based pricing methods, which do not fully integrate the intrinsic relationship between market demand and price, often resulting in overly high prices that cause demand loss or overly low prices that reduce resource value. At the same time, many ports separate priority pricing, berth allocation, and quay crane allocation into independent decision-making steps, lacking a coordinated optimization mechanism. This makes it difficult to meet the operational time constraints of ships with different priority levels, leading to berth resource conflicts and inefficient quay crane allocation. These issues not only reduce port operational efficiency but also constrain the full realization of prioritized berth usage revenue potential. In this context, developing a pricing model for prioritized berth usage rights that considers both market demand characteristics and port resource constraints, achieving coordinated optimization of pricing, berth allocation, and quay crane allocation, and ultimately maximizing port prioritized berth usage revenue has become a core issue that specialized container ports must address for market-oriented operations and refined management. This also provides a practical orientation and application scenario for this study.

This study focuses on optimizing the pricing of port berth priority usage, aiming to maximize port revenue. The total port revenue Π is the sum of basic loading and unloading service revenue Π0 and priority berth usage premium revenue ΠP, minus penalty costs Πc, that is, Π = Π0 + ΠP − Πc. The optimization goal of the model is to maximize total revenue, while simultaneously considering resource utilization efficiency, completion of loading and unloading, and penalty costs.

(1) Basic loading and unloading service revenue Π0

Basic loading and unloading revenue is the income that the port obtains from providing container loading and unloading services to ships that successfully complete loading and unloading, and it is unrelated to the ship's priority selection, berth allocation, or quay crane allocation. Its calculation is based on the product of the unit TEU basic handling fee and the ship’s loading and unloading workload, and only ships that complete loading and unloading are included in the revenue; ships that do not complete loading and unloading are not counted. Since the loading and unloading workload qi of each ship i is known, and the unit TEU basic handling fee c0 is a fixed constant, while whether a ship can complete loading and unloading depends on resource allocation and time constraints, the total basic loading and unloading revenue is:

$$\Pi_0 = c_0 \cdot \sum_{i \in I} \sum_{m \in M} \sum_{k \in K_0} q_i \cdot z_i \cdot x_{imk}$$

If a ship does not complete loading and unloading due to resource constraints or demand constraints, it is not included in this revenue. Here, ximk = 1 and zi = 1 indicate that ship i is assigned to berth m, selects the k-th priority level, and completes loading and unloading; ximk = 0 or zi = 0 indicates that the ship is not assigned a berth or is not allocated operation eligibility. Because the subsequent constraints define uniqueness and the correlation between operation eligibility and resource allocation, this implies that as long as ximk = 1, it inherently means that this ship has chosen that priority level and possesses operation eligibility. Therefore, the total basic loading and unloading revenue can be simplified as:

$$\Pi_0 = \sum_{i \in I} \sum_{m \in M} \sum_{k \in K_0} c_0 \cdot q_i \cdot x_{imk}$$

(2) ΠP of the premium income of the first right to use the berth

Premium revenue is the additional revenue obtained by the port for the provision of berth preferential use to vessels that successfully complete loading and unloading and select pricable priority (k∈K), and does not generate this revenue if the loading and unloading is not completed or the vessel without

priority (k=0) is selected. The premium income is calculated based on the product of the TEU pricing of the k-level priority unit and the loading and unloading workload of the ship selecting the gear, combined with the ship selection decision variable DIK, and the total premium income is as follows:

$$\Pi_P = \sum_{k\in K}\sum_{i\in I}\sum_{m\in M} d_{ik}\cdot z_i \cdot x_{imk}\cdot p_k \cdot q_i$$

Among them, dik=1 means that ship i chooses the priority of the k gear, and ximk=1 and zi=1 indicate that the ship has completed loading and unloading. The premium pricing PK is non-negative, which is in line with the microeconomic pricing logic, and the port will not provide a negative premium to attract ships to choose priority. In the same way, this benefit can be reduced to:

$$\Pi_P = \sum_{i\in I}\sum_{m\in M}\sum_{k\in K} p_k \cdot q_i \cdot x_{imk}$$

(3) Penalty cost Πc

For vessels that are not qualified to operate, the port is responsible for penalties for breach of contract or non-service, and the total penalty cost is:

$$\sum_{i\in I} c_{\text{pen}}\cdot q_i \cdot (1 - z_i)$$

After the introduction of penalty terms, the model has the ability to adapt to adjustment. When port berths are extremely tight, the model weighs the acceptance benefits against the refusal to punish. If the premium for accepting the high-priced vessel i is greater than the penalty for rejecting the payment of the low-priced vessel J, the model will choose zj=0. This demonstrates the dynamic filtering capabilities of priority pricing for scarce resources. The value of the penalty factor CPEN will directly affect the service level of the port. For CPEN's sensitivity analysis prediction, a larger CPEN will force the port to accept as many vessels as possible, and the model will degenerate into a hard constraint. Smaller CPEN encourages ports to adopt aggressive pricing strategies and prioritize high-yield customers.

4. ALGORITHM DESIGN

In Chapter 3, this paper constructs a pricing model for port berth priority usage. However, the model faces severe computational challenges in practical applications: first, the model introduces a discrete-time mapping technique, which causes the size of the decision variables to grow proportionally with the product of the planning horizon Tmax and the number of ships |I|. Second, the pricing decisions, priority selections, and the underlying berth-crane spatiotemporal scheduling constraints are highly coupled, making it difficult for traditional Branch and Bound algorithms to provide satisfactory solutions within a reasonable time for large-scale instances.

To address such problems with a 'allocation-scheduling' two-layer structure, this chapter designs a Logic-Based Benders Decomposition (LBBD) algorithm. Unlike traditional Benders decomposition, which relies on the linear programming duality of the subproblem, LBBD allows the subproblem to include complex logical constraints, discrete variables, or nonlinear terms, and iteratively solves the problem by establishing logic cuts between the Master Problem (MP) and the Subproblem (SP). The master problem is responsible for macro-level pricing and initial berth allocation, while the subproblem, given a fixed allocation scheme, verifies spatiotemporal conflicts and resource balance at the physical level. This 'divide-and-conquer' strategy can significantly reduce the search space and improve computational efficiency.

5. CONCLUSION

Compared with ordinary port scheduling schemes, the priority scheme can increase port revenue through layered service commitments and an endogenous price selection mechanism. Moreover, the results indicate that the berth priority pricing mechanism can effectively support ports in providing differentiated services and revenue management under conditions of resource scarcity.

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