Scientific and Social Research, 2023, Volume 5, Issue 10
https://ojs.bbwpublisher.com/index.php/SSR

Analysis of Berth Allocation Problems of Mainline and Feeder Vessels due to Ship Delays

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Abstract: With the development of the shipping industry, port terminals are becoming increasingly busy. As an essential resource at the front of the terminal, berths are responsible for connecting the seaside and landside of the port. The efficiency of loading and unloading operations depends very much on the berth allocation. However, due to certain events such as weather factors and ship failures, ships are often delayed in arriving at the port, which severely impacts the berth allocation plan. To effectively deal with the effects of ship delay on the berth allocation plan, this paper studies the berth allocation problem of mainline and feeder vessels, considering the impact of uncertainty.

Keywords: Port management; Berth allocation; Mainline and feeder vessels; Ship delay

Online publication: October 20, 2023

I. Introduction

Berths are one of the core resources at the terminal front, and the issue of berth allocation has always been the research focus of many scholars. Berths can be divided into continuous and discrete berths according to their types. A continuous berth is a continuous shoreline wall with no clear division between berths, while discrete berths are independent.

Kim and Park [1] began to study issues related to berth allocation as early as 2003. Han and Zhao [2] considered the priority weight of ships with different loads, corresponding this priority to the ship's time in port, and established a constraint and mixed integer programming model. Xie *et al.* [3] studied the discrete berth allocation problem, launched an integer programming model to minimize the total cost of ship berth offset and time offset, and designed three branch pricing algorithms with different initial column generation methods. Zeng *et al.* [4] considered the loading and unloading priorities of mainline and feeder vessels, established a mixed integer programming model, and designed a heuristic algorithm.

Whether a ship can finish loading and unloading on time depends on whether it docks at the berth. Therefore, berth allocation needs to be considered from a dynamic perspective so that the berth allocation plan has a specific anti-interference ability. To reduce interference on the container terminal operating system and related costs, Zeng and Zhang [5] studied the issue of how to adjust the berth allocation plan due in the event of interference in container terminals and quay crane scheduling plans. They measured system disruptions from various angles and built a model for managing these interferences.

The aforementioned studies have examined the berth allocation problem both in static and dynamic contexts. While certain scholars have delved into prioritization within berth allocation, they have not addressed the dynamic scenario where the priority of mainline and feeder vessels comes into play.

2. Problem description

In actual operations, the container terminal will collect berthing ship information in advance within a fixed operation plan period and then formulate an initial operation plan based on the berthing duration of the ship and the prioritization of the ships. Large ships are usually the mainline vessels. The mainline vessels are mainly responsible for transporting large quantities of import boxes and unloading them at the dock to complete the import. Feeder vessels are generally small ships, which are mainly responsible for unloading mainline vessels and diverting import boxes. Therefore, when formulating a berth allocation plan, mainline vessels have higher priority than feeder ships.

In the operation of frontier terminals, some ships might experience delays in reaching the port due to unpredictable events like adverse weather or sea blockades. Upon receiving information about such delays, the terminal must act promptly to adapt the ship's berth allocation plan accordingly. As the completion of loading for feeder vessels hinges on mainline vessels finishing unloading first, it is essential to take into account the priority order between mainline and feeder ships when making adjustments to the ship's berth allocation plan.

In summary, this article addresses the research problem as follows: A container terminal initially creates a berth allocation plan within a set planning period upon receiving ship arrival details. However, uncertainties during the project execution can lead to ship delays. Taking into account the priority of mainline and branch line ships, a berth reallocation plan is devised to minimize ship delay costs and offset the initial berth expenses within the planning period.

3. Mathematical model

3.1. Model assumptions

(i) The impact on the ship's balance during loading and unloading operations is not considered; (ii) the influence of tides and waterways on the entry and exit of the ship are not considered; (iii) the information of the ship's original operation plan is known.

3.2. Symbol description

S is the gathering of mainline vessels arriving at the port (including delayed ships); Q is the gathering of branch line ships; i, j is the shipping number. If the main line ship (j) corresponding to the feeder vessel is i, θ_{ij}, is 1; otherwise, it is 0. l_i is the length of ship i; h_i is the loading and unloading time of the ship i; L is the total length of the line. Ship i's arrival time is T_i^{arrive}; the ship i's original expected departure time is T_i^{leave0}; ship i's waiting time for berthing is T_i^{wait}; the ship i's actual unberthing time is T_i^{leave}. Ship i's original planned berthing position is P_i; the exact berth position of ship i after adjusting the initial plan is p_i. M is a large enough constant; C_1 is the unit cost of deviating from the original berth; C_2 is the unit time penalty cost of the ship's demurrage. If the berthing time of the ship j is later than the ship i, xt_{ij} is 1; otherwise it is 0. If the berth position of the ship i is on the right side of the ship j, xl_{ij} is 1; otherwise, it is 0.

3.3. Model constraints

$$minF = \sum_{i \in S,Q} C_1 \Delta_i + C_2 (T_i^{leave} - T_i^{leave0}) \quad (1)$$

$$p_i + \frac{l_i + l_j}{2} \leq p_j + M(1 - xl_{ij}), \forall i \in SVQ, \forall j \in SVQ, i \neq j \quad (2)$$

$$T_i^{arrive} + T_i^{wait} + h_i \leq T_j^{arrive} + T_j^{wait} + M(1 - xt_{ij}), \forall i \in SVQ, \forall j \in SVQ, i \neq j \quad (3)$$

$$xt_{ij} + xt_{ji} + xl_{ij} + xl_{ji} \geq 1, \forall i \in SVQ, \forall j \in SVQ, i \neq j \quad (4)$$

$$\frac{l_i}{2} \leq p_i \leq L - \frac{l_i}{2}, \forall i \in SVQ \quad (5)$$

$$T_i^{leave} = T_i^{arrive} + T_i^{wait} + h_i, \forall i \in SVQ \quad (6)$$

$$\Delta_i \geq |P_i - p_i|, \forall i \in SVQ \quad (7)$$

$$\Delta_i \geq |p_i - P_i|, \forall i \in SVQ \quad (8)$$

$$[(T_i^{arrive} + T_i^{wait}) - (T_j^{arrive} + T_j^{wait})]\theta_{ij} \leq 0, \forall i \in 0, \forall j \in 0 \quad (9)$$

$$p_i \in [1, L] \quad (10)$$

$$xt_{ij}, xt_{ji}, xl_{ij}, xl_{ji} \in \{0, 1\} \quad (11)$$

The objective function (1) represents the cost associated with minimizing the ship's deviation from its initial berthing position, as well as minimizing the delay cost. Constraints (2) to (4) specify that the distance between any two ships during berthing should not exceed the total length of the berth. Additionally, these constraints address operational conflicts between any two ships. Equation (6) represents the ship's unberthing time; Constraints (7) and (8) linearly represent the length of the ship's offset berth. Constraint (9) represents the correspondence between mainline vessels. The feeder vessels of must be able to berth after the mainline vessels berth. Constraints (10) and (11) determine the acceptable value ranges for the decision variables.

4. Case analysis

In this scenario, the article took 24 hours as a fixed planning period, and the pier length was 1200 meters. A total of ten ships arrived at the port during the planning period, including three mainline ships (Ship 1, Ship 2, and Ship 3), and the rest were feeder ships. The initial berth plan of the ship is shown in **Table 1**. A mainline vessel and a feeder vessel were randomly selected from the planning period, and a mathematical programming solver is used to solve the problem. The adjustment plan is shown in **Table 2**, with C_1 was set to 50, C_2 set to 2000, and the objective function value was 12800.

Table 1. Initial berth allocation plan

Ship number	Captain (m)	Homework duration	Arrival time	Departure time	Berthing position
1	260	13	0	13	1040
2	280	10	1.5	11.5	750
3	200	12	2	14	300
4	120	8	3.5	11.5	520
5	150	10	12	22	100

Table 1 (continued)

Ship number	Captain (m)	Homework duration	Arrival time	Departure time	Berthing position
6	200	9	14	23	1070
7	120	8	13	21	800
8	110	8	13.5	21.5	605
9	120	9	14.75	23.75	420
10	130	6	14.75	20.75	265

Table 2. Adjusted berth allocation plan

Ship number	Captain (m)	Homework duration	Arrival time	Departure time	Berthing position
1	260	13	0	13	1040
2	280	10	6.5	16.5	730
3	200	12	2	14	330
4	120	8	3.5	11.5	520
5	150	10	14	24	100
6	200	9	14	23	1090
7	120	8	13	21	930
8	110	8	13.5	21.5	535
9	120	9	14.75	23.75	420
10	130	6	14.75	20.75	265

5. Conclusion

In this paper, we investigated the berth allocation problem for both mainline and feeder ships, taking into account potential delays. Then, we developed a mixed-integer linear programming model that incorporates the priority of mainline and feeder ships, translating it into mathematical constraints. The model's efficacy was confirmed through the solution of an illustrative example, which demonstrated its ability to effectively handle ship delays.

In future research, the impact of waterway conditions on ships entering and leaving the port can be examined, and the integrated optimization of scheduling for both waterways and berths can be considered.

Disclosure statement

The author declares no conflict of interest.

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