E3S Web of Conferences 512, 04029 (2024) https://doi.org/10.1051/e3sconf/202451204029
UCT 2024

Route Optimization of Grain Fleet Considering Bunker Cost

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Abstract. To minimize grain fleet operational costs, we employ a route optimization approach that considers bunker costs. A mixed-integer programming model is created, factoring in the unique features of bulk grain shipping and varying oil prices at bunker ports. The goal is to optimize the fleet's transportation route, with decision variables encompassing bunker port selection, bunker volume, and ship navigation path. Using a dry bulk cargo company's grain transport fleet as a case study, the Gurobi solver validates the model's effectiveness. Results reveal that, excluding the loading port, the grain fleet can select low oil price ports along the route for bunkering. Optimal cost reduction is achieved by choosing multiple bunker ports and increasing bunker quantity. Additionally, the model harmonizes port charges with bunker costs, refining the grain fleet's transportation route and effectively managing operational expenses.

1. Introduction

Dry bulk shipping constitutes 40% of global cargo transport, with grain accounting for over 10% of total sea dry bulk shipping, following iron ore and coal. Grain is typically transported by unscheduled vessels through a contract between the carrier and trustee. Operating costs for grain ships involve fuel, fixed expenses (staffing, leasing), and port fees (tonnage tax, etc.), with fuel costs sometimes exceeding 50% of operational expenses. Fluctuating international situations impact fuel prices, varying across ports and over time. Choosing an optimal bunkering port during grain ship transportation can significantly cut costs, underscoring the practical importance of such research.

Currently, most studies on grain transportation, both domestically and internationally, primarily focus on railroad container transport, land modes like public-rail intermodal transport, and grain supply chain security[1]. While some scholars have delved into grain maritime transportation, their emphasis has been on the capacity and layout of grain ports rather than the shipping paths of grain vessels[2]. Grain maritime transportation belongs to dry bulk transportation, which is usually carried out by unscheduled ships. The academic community has made abundant research results on the transportation path problem of unscheduled ships for dry bulk cargoes, and Appelgren[3] put forward the unscheduled ship path optimization problem for the first time, which laid the foundation for later research in the transportation path of unscheduled ships. Subsequent research directions of scholars have focused on cargo factors in irregular ship path optimization. Korsvik[4] and Lin[5] studied the problem of flexibility in cargo selection during ship transportation so as to improve the profitability of ship transportation; Bronmo[6] and Thompson[7] studied the problem of cargo size and the composition of the number and product units of each cargo batch, which further reduced the cost of ship transportation and improved the efficiency of transportation. Scholars have extensively researched the path optimization of dry bulk carriers, considering practical aspects. Fuel, a significant factor affecting shipping costs and environmental impact, has garnered attention due to its substantial share in operational costs. Recent discussions among scholars have focused on addressing fuel cost concerns. Jia Peng[8] et al. used AMRA model for the first time to forecast fuel prices and established a nonlinear programming model with the objective of maximizing the revenue of shipping companies, and the results showed that shipping companies can effectively reduce costs by incorporating fuel price fluctuations into the path optimization; Qiang Meng[9] et al. combined the fuel replenishment of ships with the demand problem of spot cargo in the irregular ship transportation problem to optimize the ship path problem and increase the revenue of shipping companies. increased the revenue of shipping companies; then, Chunjuan Wang[10] integrated speed optimization with continuous voyage fuel replenishment. They introduced a unified scheduling problem for irregular ship routes, employing a multiple nested expectation method to dynamically model oil price dynamics. This approach effectively balances actual cargo and fuel replenishment volumes, enabling precise revenue and cost control across multiple continuous voyages.

Existing literature predominantly focuses on land transportation, grain supply chain security, and grain port capacity in grain transportation research. However, there

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is a notable gap in addressing grain ship transportation route issues. Current research on dry bulk cargo transportation route optimization often neglects fuel costs in route selection. This study aims to fill these gaps by examining the impact of spatial and temporal variations in oil prices on ship path planning. We propose optimizing grain ship transportation paths by strategically selecting refueling ports and volumes to reduce costs and enhance efficiency, contributing valuable insights to grain ship transportation path planning.

2. Problem description

Grain shipping, characterized by unpredictable routes and voyage periods, faces challenges like sinking and scattering of bulk grain, impacting ship safety. The transportation route significantly influences operating costs. Optimizing bulk grain shipping routes helps reduce overall operating costs, with fuel costs constituting a major portion, typically around 50%. Fuel costs vary spatially and temporally, affecting different ports simultaneously and fluctuating within the same port at different times. Considering these challenges, this study focuses on the temporal and spatial variability of fuel prices and replenishment costs. It proposes a mixed integer planning model to optimize fleet paths, aiming to lower operational expenses and enhance transportation efficiency.

On the premise of considering the particularity of grain, this paper designs a directed space-time network $\mathbf{G}=(\mathbf{N},\mathbf{A})$ including node set $\mathbf{N}$ and arc set $\mathbf{A}$ for grain transportation during the planning period. Among them, $\mathbf{N}=\{1,\ldots,n\}$ represents the collection of nodes in the transport network, and nodes refer to the ports, straits and canals that ships may pass through on a certain day in the process of transportation, in which node coordinates include two attributes: time and space. In this paper, the starting node set $\mathbf{O}=\{o_1,o_2,\ldots,o_k\}$ and the arrival node set $\mathbf{D}=\{d_1,d_2,\ldots,d_k\}$ are set for the ships in the dry bulk carrier fleet $\mathbf{T}=\{t_1,t_2,\ldots,t_k\}$ during the planning period, which indicates the transport path of the ships in the fleet during the planning period. $\mathbf{A}=\{a_1,a_2,\ldots,a_m\}$ represents the set of network arcs between nodes, in which each network arc $a=(i,j)$ has a corresponding weight vector $W_{ij}=(u_{ij},v_{ij})$, which represents the fuel cost u_{ij} of the ship from node i to node j and the fixed cost v_{ij} of the ship from node i to node j, as shown in figure 1 below. In Figure 1, the ship moves grain from the loading port to the unloading port, strategically choosing a refueling port at the optimal time during transportation. The known sailing distances between nodes in the transportation network allow calculation of fuel consumption and operating costs based on ship parameters.

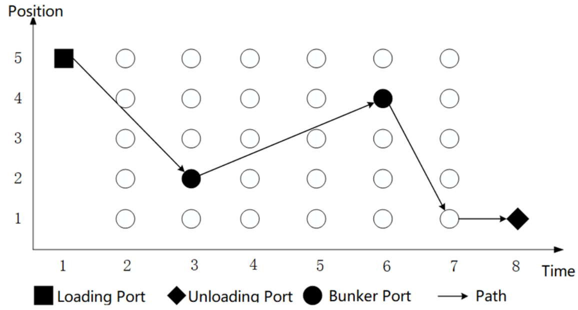

Figure 1. Spatial and temporal network diagram of grain shipping

3.Model formula

3.1.Model hypothesis

(1) The time spent by the ship in port operations is not taken into account.;

(2) ships sail at an economic speed during the planning period;

(3) the influence of ship fuel and cargo weight on ship fuel consumption is not considered;

(4) the fleet is composed of the same type of ships, all of which are convenient ships.

3.2.Symbol description

(1)Set

$\mathbf{G}$: the time and space network of grain shipping

$\mathbf{N}$: the collection of all nodes, including ports, straits, and canals

$\mathbf{A}$: the collection of network arcs between nodes

$\mathbf{O}$: the set of starting nodes in the time-space network

$\mathbf{D}$: the set of arriving nodes in the time-space network

$\mathbf{T}$: the set of transport paths for a ship from the start node to the arrival node

$\mathbf{K}$: the set of ships in a fleet

$\mathbf{E}$: the set of goods in the grain shipping contract

(2)Parameter

i,j : the node number, $i,j\in\mathbf{N}$

k : the ship number, $k\in\mathbf{K}$

e : the cargo number in grain shipping contract, $e\in\mathbf{E}$

c_{ij}^{k} : is the fixed cost required for ship k to travel from node i to node j

g_i : the port make fee for node i

d_{ij}^{k} : the fuel consumption of ship k from node i to node j

p_i: the fuel price at node i. If i is a strait or a canal, then p_i is an extreme value M

h^k: the tank capacity of the ship k

q^k: the maximum deadweight tonnage of the ship k

w_e^k: The weight of order e transported by ship k

α: the bunker safety factor to ensure the normal operation of the ship

β: the ship bunker oil ceiling factor

γ: the vessel initial oil quantity factor

θ: the safe load factor for grain ships

M: the maximum value

(3) Variable

s_i^k: the remaining oil quantity of ship k at node i

x_{ij}^k: whether ship k travels from node i to node j. If ship k travels from node i to node j, then $x_{ij}^k = 1$, otherwise $x_{ij}^k = 0$

y_i^k: whether ship k replenishes fuel at node i. If ship k replenishes fuel at node i, then $y_i^k = 1$, otherwise $y_i^k = 0$

z_i^k: refueling of ship k at node i. If ship k refuels at node i, then $z_i^k > 0$, otherwise $z_i^k = 0$

3.3. Mathematic model

According to the description of the previous problem, in order to minimize the operating cost of the grain fleet of a single shipping company, this paper constructs the following mixed integer programming model:

$$\min Z = \sum_{k\in\mathbf{K}}\sum_{(i,j)\in\mathbf{A}} x_{ij}^k * c_{ij}^k + \sum_{k\in\mathbf{K}}\sum_{i\in\mathbf{N}} p_i * z_i^k + \sum_{k\in\mathbf{K}}\sum_{i\in\mathbf{N}} g_i * y_i^k \tag{1}$$

$$\text{s.t.} \quad \sum_{j|(i,j)} x_{ij}^k - \sum_{j|(j,i)} x_{ji}^k = 1 \quad k\in\mathbf{K}, i\in\mathbf{O} \tag{2}$$

$$\sum_{j|(i,j)} x_{ij}^k - \sum_{j|(j,i)} x_{ji}^k = -1 \quad k\in\mathbf{K}, i\in\mathbf{D} \tag{3}$$

$$\sum_{j|(i,j)} x_{ij}^k - \sum_{j|(j,i)} x_{ji}^k = 0 \quad k\in\mathbf{K}, i\in\mathbf{N}, i\notin\mathbf{O},\mathbf{N} \tag{4}$$

$$(s_j^k - s_i^k + z_i^k - d_{ij}^k * x_{ij}^k) * x_{ij}^k = 0 \quad k\in\mathbf{K}, (i,j)\in\mathbf{A} \tag{5}$$

$$s_i^k + z_i^k \le h^k \quad k\in\mathbf{K}, i\in\mathbf{N} \tag{6}$$

$$0 \le z_i^k \le h^k * \sum_{j|(i,j)} x_{ij}^k \quad k\in\mathbf{K}, i\in\mathbf{N} \tag{7}$$

$$s_i^k \ge \alpha * h^k \quad k\in\mathbf{K}, i\in\mathbf{N} \tag{8}$$

$$s_i^k \le \beta * h^k \quad k\in\mathbf{K}, i\in\mathbf{N} \tag{9}$$

$$s_i^k = \gamma * h^k \quad k\in\mathbf{K}, i\in\mathbf{O} \tag{10}$$

$$w_e^k \le q^k * \theta \quad k\in\mathbf{K}, e\in\mathbf{E} \tag{11}$$

$$x_{ij}^k \in \{0,1\} \quad k\in\mathbf{K}, (i,j)\in\mathbf{A} \tag{12}$$

$$y_i^k \in \{0,1\} \quad k\in\mathbf{K}, i\in\mathbf{N} \tag{13}$$

Formula (1) represents the objective function, aiming to minimize the ship's operating cost. The operating cost comprises three components: the fixed cost (crew wages and ship depreciation), fuel cost, and port cost, with the latter encompassing both port service and pilotage fees. Formula (2)-(4) the flow balance constraint of the ship in the transport network. Formula (5) ensures the continuity of the oil quantity of the ship's oil tank; formula (6) means that the sum of the ship's remaining oil and refueling capacity is not higher than the tank volume; formula (7) ensures that the ship refuels only at the nodes in the transport path. Formula (8) ensures that the oil content of the ship's oil tank is always not lower than the lower limit of tank safety, and formula (9) ensures that the amount of oil in the ship's oil tank is never higher than the upper limit of oil tank safety; formula (10) indicates the initial oil quantity of the ship's oil tank; formula (11) is the grain ship load constraint, which ensures that the grain weight of the order is not higher than the upper limit of the ship's safe load. Formula (12)-(13) is a 0-1 variable constraint.

4. Example analysis

The fleet of an ocean dry bulk cargo company has three convenient grain carriers, numbered 1-3. The specific data of the ships are shown in Table 1 below. During the 30-day planning period, the company has signed five grain transportation contracts, numbered 1-5, and its loading and unloading ports are all important grain ports in the world. it involves San Francisco in North America, Qinhuangdao and Hong Kong in East Asia, Ho Chi Minh and Bangkok in Southeast Asia, Kendra in South Asia, and Foss and Odessa in Europe.

The specific loading and unloading ports are shown in Table 2 below.

Table 1. Ship data

Vessel number	Economy speed/Mile	Fuel tank volume/t	Daily fuel consumption of ships/t	Vessel daily fixed costs/USD	Vessel deadweight tonnage/t
1	13.9	453.5	24.9	2117.4	31775
2	13.9	434.2	25.3	2118.3	31761
3	13.9	437.5	23.1	2119.7	32005

Table 2. Transportation tasks

Vessel number	Contract of carriage number	Port of loading	Port of discharge	Order grain weight /t
1	1	San Francisco	Ho Chi Minh	26998
1	2	Ho Chi Minh	Candela	26654
2	3	Foss	HK	26886
3	4	Qinhuangdao	Bangkok	26985
3	5	Bangkok	Odessa	26768

4.1.Result analysis

The Gurobi solver is used to solve the model directly under the environment of Python 3.7. The optimal solution of the model is measured under Intel (R) Core (TM) i7-9750H CPU @ 2.60GHz 2.59 GHz and 8G memory platform, and the accuracy of the model is verified. Assume that the port usage fee of all ports is 40000 USD and $\alpha = 15\%$, $\beta = 80\%$, $\gamma = 20\%$, $\theta = 85\%$. The optimized results of the model are shown in Table 3.

Table 3. Calculation results

Vessel number	Path	Bunker port	Bunker quantity/t
1	San Francisco - Soya Strait - Taiwan Strait - Ho Chi Minh - Malacca Strait - Candela	San Francisco	327.42
		Busan	174.30
		Singapore	199.20
2	Foss- Strait of Gibraltar - Strait of Tunis - Suez Canal - Strait of Mande - Malacca Strait -HK	Foss	347.60
		Alexandria Port	161.98
		Colombo	202.40
3	Qinhuangdao - Taiwan Strait - Bangkok - Malacca Strait - Strait of Mande - Suez Canal - Black Sea Strait - Odessa	Qinhuangdao	231.42
		Singapore	294.77
		Colombo	121.02

As can be seen from Table 3, ship 1 replenishes 327.42t of fuel at the initial port San Francisco, 174.30t of fuel at Busan, and 199.20t of fuel at Singapore; ship 2 replenishes 347.60t of fuel at the initial port Foss, 161.98t of fuel at Suez Canal, and 202.40t of fuel at Colombo; ship 3 replenishes 231.42t of fuel at the initial port Qinhuangdao It is obvious that the ships replenish fuel at the ports near the routes in the transportation network with lower fuel prices, except for the initial port where they replenish fuel.

4.2.Sensitivity Analysis of fuel Price

The international fuel price fluctuates a lot, which affects the ship fuel cost and thus the ship operation cost also changes. Therefore, the sensitivity analysis of operating cost can be carried out according to the change of fuel price, and 11 sets of arithmetic cases are constructed by increasing fuel price from 95% to 105%, and the results are shown in Figure 2.

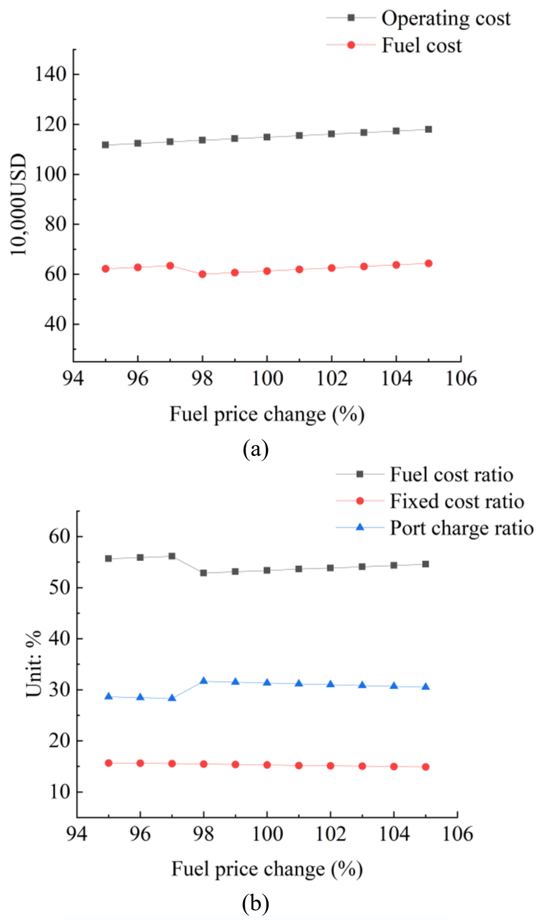

Figure 2. Fuel price sensitivity analysis

In Figure 2(a), bunker costs generally increase but show local decreases. Operating costs rise with bunker prices from USD 1,117,200 to USD 1,179,400. A strategic decision to increase bunker ports from 8 to 9 at a 98% fuel price results in an average bunker price drop by 8.197 USD/ton, reducing bunker costs from US$634,500 to US$60,700. The remaining period sees a rising trend in bunker costs. In Figure 2(b), overall fuel cost percentages increase with fuel prices, while port making fees decrease overall but increase locally. A 98% fuel price leads to a 3.28% decrease in fuel cost share and a 3.36% increase in port cost share. The subsequent period sees increasing fuel cost share and decreasing port cost share trends. The fixed cost ratio decreases slightly from 15.68% to 14.91% with rising fuel prices. In summary, when bunker prices are on the rise, strategically choosing bunker ports can effectively reduce fleet bunker costs.

5.Summary

This paper explores the impact of spatial and temporal variations in fuel prices on the fuel replenishment cost in the context of grain shipping. Our aim is to optimize grain fleet transportation paths, minimizing overall operational costs. The study addresses the grain fleet path optimization problem, incorporating fuel replenishment strategies. We use a mixed-integer programming model, employ the Gurobi solver, conduct sensitivity analysis, and draw the following conclusions:

1.During maritime transportation, grain fleets can reduce fuel costs and control operational expenses by strategically selecting fuel replenishment ports and volumes. This includes opting for ports with lower fuel prices along the transportation route, in addition to loading ports.

2.Faced with rising fuel prices, shipping companies can adjust the safety coefficient of ship bunkering, initial fuel quantity coefficient of ships, or increase the number of fuel replenishment ports to effectively manage fuel costs. However, the increase in fuel replenishment ports is accompanied by higher port charges. Therefore, shipping companies must carefully balance the relationship between the average price of fuel replenishment and the number of fuel replenishment ports, considering the interplay with port charges, to achieve the dual objectives of reducing fuel costs and controlling operational expenses.

Acknowledgments

This study was supported by the China National Social Science Foundation under the "Research on the Innovation of Maritime Border Management System to Serve the Strategy of Strong Ocean State" (Project No. 18VHQ005).

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