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Fleet Repositioning, Flag Switching, Transportation Scheduling, and Speed Optimization for Tanker Shipping Firms

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Abstract: In response to the European Union (EU)'s sanctions on Russian oil products, tanker shipping firms may adopt two strategies to reoptimize their shipping networks. The first strategy is to switch the flag states of tankers that are not eligible to operate on certain routes. The second strategy is to reposition tankers based on their flag states, i.e., moving those tankers that are eligible from other groups to specified routes. To help tanker shipping firms minimize the total operating cost during the planning horizon in the context of EU oil sanctions, including costs of fleet repositioning, flag switching, and fuel, this study investigates an integrated problem of fleet repositioning, flag switching, transportation scheduling, and speed optimization considering the dynamic relationships among fuel consumption, speed, and load. By formulating the problem as a nonlinear integer programming model and applying various linearization techniques to convert the nonlinear model into a linear optimization model solvable by off-the-shelf linear optimization solvers, this study demonstrates the practical application potential of the proposed model, with the longest solution time of less than two hours for a numerical instance with seven routes. Furthermore, through sensitivity analyses on important factors including unit fuel prices, crude oil transportation demand, and the tanker repositioning cost, this study provides managerial insights into the operations management of tanker shipping firms.

Keywords: tanker shipping; flag switching; fleet redeployment; EU oil sanctions

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1. Introduction

Crude oil, a vital natural resource, is widely used in global economic operations and daily life, and has a significant impact on modern society [1,2]. As the cornerstone of modern industry and transportation systems, it supports the efficient operation of the global transportation network through its conversion into various fuels such as gasoline, diesel, and aviation fuel [3]. More importantly, as the primary raw material for many chemicals and synthetic materials, applications of crude oil span a broad range of fields, from plastics to synthetic fibers and from pharmaceuticals to personal care products [4]. In agriculture, fertilizers and pesticides derived from crude oil significantly increase the efficiency of food production [5]. Given its irreplaceable importance, fluctuations in its market price often greatly affect the global economy [6]. In early 2020, as the COVID-19 pandemic spread globally, many countries implemented lockdown measures to halt the spread of the virus, leading to a steep drop in worldwide demand for crude oil [7]. In April 2020, the price of West Texas Intermediate (WTI) crude oil dropped to USD −37.63 per barrel [8]. This price collapse exerted severe economic pressure on countries reliant on oil exports. At the same time, the plunge in energy prices led to a decrease in global inflation rates, reflecting the profound impact of the crude oil market on the global economy [9].

The crude oil market constructs a vast and complex global trading network that covers important areas such as the production, transportation, and trading of crude oil. This market is extremely sensitive to geopolitical changes, especially events like wars, political instability, economic sanctions, and international agreements. These factors may lead to interruptions in crude oil supply or trigger market expectations of fundamental changes, thereby causing severe fluctuations in crude oil prices. Taking the Russia–Ukraine War as an example, the price fluctuation of WTI crude oil went up to 70.72%, while the price change of Brent crude oil reached 73.62% [10]. Given that Russia is the global third largest crude oil producer [11], the European Union (EU)'s energy export sanctions are particularly significant. Specifically, the EU decided to ban imports of Russian crude oil and petroleum products, including a complete prohibition on seaborne crude oil imports [12]. These sanctions not only directly affect Russia's energy exports, but also stimulate widespread concern about energy supply security globally, thus having a profound impact on the crude oil market. This impact extends beyond price fluctuations and profoundly reshapes the global energy economy.

In the context of the EU's sanctions on Russian oil exports, tanker shipping firms must carefully take into account flag states of their tankers to optimize their crude oil transportation services. The flag a ship flies not only indicates its registration with that country but also means that the country is the ship's flag state [13]. Before the implementation of EU oil sanctions, the flag state of a tanker often had little impact on the fleet deployment strategy. However, to effectively respond to EU oil sanctions, it has become a common practice to consider tanker flag states to rationally re-allocate ships to different crude oil transportation routes. Moreover, changing the flag, i.e., changing the tanker's registered nationality, has also become an effective strategy for tanker shipping firms to cope with EU oil sanctions. Particularly for routes between the EU and Russia, the above two practices can minimize the idle cost of tankers and avoid investments in purchasing new tankers to expand the fleet. By flexibly adjusting tanker flag states and fleet deployment, tanker shipping firms may more effectively respond to changes in the international political situation, ensuring operations efficiency and cost-effectiveness.

To deal with the new challenges arising in crude oil transportation, this study investigates a fleet redeployment problem considering the flag switching strategy and crude oil transportation scheduling. This is a complex issue where various decision-making aspects are interdependent and interact with each other: the flag state of a tanker not only affects fleet deployment decisions, but also further influences decisions regarding flag switching, fleet repositioning, crude oil transportation scheduling, and speed optimization. Moreover, the sailing speed of a tanker directly relates to the completion of voyages, and the planning of voyage completions is closely related to the scheduling of crude oil transportation. In this context, adopting quantitative methods to study this problem is particularly important. By adopting the method proposed in this study, tanker shipping firms can make decisions on optimizing fleet repositioning, crude oil transportation, flag switching, and speed adjustment, thereby minimizing the total cost including the costs of flag switching, tanker repositioning, and fuel. This approach enables tanker shipping firms to operate more flexibly and efficiently in response to the dynamics of the global energy shipping market.

The structure of this study is outlined as follows. Section 2 discusses previous research. Section 3 analyzes the problem, formulates a nonlinear integer programming (IP) model, and employs various linearization techniques to linearize the model. Section 4 details the results of numerical experiments. Conclusions are summarized in Section 5.

2. Literature Review

In recent years, the topic of fleet redeployment (repositioning) has attracted widespread academic attention, as evidenced by notable studies such as [14–18]. This increased focus stems from the need for shipping lines to optimize their current liner shipping service networks every three to six months. Similar to fleet deployment and service network optimization in liner shipping, these strategies can be effectively applied to tanker shipping as well, especially given the changing market conditions and geopolitical developments. This optimization is critical to adapt to the fluctuating demands of crude oil transportation, ensuring that services respond to market needs. This section begins by reviewing the evolution of research in the field of combining fleet deployment and fleet redeployment (repositioning). Following this, we discuss several operations management factors closely related to fleet deployment to comprehensively understand the complexity and multi-dimensional impacts of this issue in the context of modern shipping management.

Due to policy adjustments or the uncertainty of market demand, fleet redeployment (repositioning) becomes necessary. Research on the fleet redeployment (repositioning) problem has developed over many years. Ref. [14] focused on the fleet repositioning problem without considering demand flows, developed three approaches to solve the problem, and tested them using a real-world instance dataset. Ref. [19] analyzed the effectiveness of constraint programming and lazy clause generation compared to a solve-and-improve approach for the fleet repositioning problem, finding both methods efficient. Ref. [15] proposed a mixed integer programming (MIP) model to reallocate ships and design cargo routes, aiming to minimize total costs and optimize liner service networks. Building on Ref. [14], Ref. [16] formulated an optimization model and designed a simulated annealing algorithm for the fleet redeployment problem with cargo glows. Their numerical results demonstrated that the proposed algorithm has great potential to be used in decision support systems. Ref. [20] reviewed both the fleet deployment problem and the fleet redeployment (repositioning) problem, discussing how to integrate and model repositioning. Ref. [21] combined fleet deployment with repositioning to improve liner networks, using real-world sized computational instances and providing managerial insights that optimizing deployment and repositioning simultaneously can significantly reduce costs over addressing the problems independently.

Fleet deployment involves numerous factors. This study reviews the existing literature with a specific focus on planning methods that cover speed optimization, cargo flows, ship capacity restriction, and flag switching strategies during the deployment of fleets. First, sailing speed is identified as a key determinant of the operational costs for liner fleets, a point emphasized in Ref. [22]. Speed optimization receives extensive attention in research. Ref. [23] evaluated the cost-effectiveness of reducing ship speed as a strategy for decreasing carbon dioxide emissions at U.S. ports. Ref. [24] formulated a cost model to analyze the trade-off between slowing steaming and increasing fleet size on a route, suggesting a method to determine the optimal fleet size and sailing speed for minimizing annual operational costs. By utilizing published data, the research illustrated the significant cost-saving potential achievable by operating at or near the optimal cost-minimizing speed. Second, in the context of fleet deployment, cargo flows are another critical consideration that must be factored into the decision-making process. Ref. [25] conducted a detailed analysis on cargo allocation, speed optimization, and fleet deployment, targeting the maximization of overall profit from a strategic perspective. Third, ship capacity restriction is an important factor influencing the total cost associated with fleet deployment. Ref. [26] presented an MIP model adapted to the fleet deployment problem of the Panama Canal and argued that reallocating large ships to Canal-crossing routes could positively affect the total operational costs. Additionally, flag switching is a strategy employed by tanker shipping firms to circumvent EU oil sanctions, highlighting the need for research into fleet repositioning that incorporates flag switching, a topic currently overlooked in the literature. Ref. [27] first pinpointed new difficulties in fleet redeployment triggered by EU oil sanctions and developed a nonlinear IP model to tackle this comprehensive issue, including aspects like speed optimization, fleet deployment, round trip completion, and fleet redeployment. Notably, while Ref. [27] took into account the flag states of tankers, their model allowed for only one approach to dealing with the challenges introduced by EU oil sanctions. Building on Ref. [27], this study introduces two strategies: repositioning tankers across different routes considering flag states, and switching the flag states of tankers deployed in EU–Russia regions. These two strategies, by facilitating the efficient utilization of tankers and reducing the need for new investments, can significantly lower both the idle costs of tankers and the investment cost of purchasing new tankers.

In summary, tanker shipping firms need to optimize their fleet deployment strategies to deal with policy changes or uncertainties in market demand. Currently, there is little research integrating fleet repositioning, crude oil transportation scheduling, and speed optimization. Furthermore, the literature lacks discussion on the application of flag switching in fleet repositioning, and the dynamic relationship among fuel consumption, speed, and load. As far as we are aware, this study is the first attempt to bridge this research gap through the development of a nonlinear IP model. This model is designed to optimally manage fleet repositioning, transportation scheduling, flag switching, and tanker sailing speeds, with the goal of minimizing overall costs, which include the tanker flag switching cost, the repositioning cost, and the fuel cost.

3. Model Formulation

Starting from 5 December 2022, the EU has implemented sanctions against Russian oil products, prohibiting the import of Russian crude oil transported by sea [12]. Consequently, EU-flagged ships can no longer carry Russian crude oil, compelling tanker shipping firms to reoptimize their shipping services while considering flag states of their tankers. In addition to ship repositioning between different routes considering flag states of tankers, flag switching is another way tanker shipping firms are responding to the oil sanctions. Faced with the new challenges brought about by the EU oil sanctions, this study proposes a nonlinear IP model. This model aims to provide a scientific quantitative method for tanker shipping firms to jointly optimize fleet repositioning, flag switching, crude oil transportation scheduling, and speed optimization. Detailed analysis of the problem is provided in Section 3.1, while Section 3.2 outlines the nonlinear model developed to address the problem. To linearize the previous nonlinear model, some linearization methods are applied in Section 3.3.

3.1. Problem Analysis

This study examines a tanker shipping firm affected by EU oil sanctions. Before EU oil sanctions, the firm originally provided long-term and stable crude oil shipping services along a set R of routes, indexed by r, and managed a set H of tanker groups, indexed by h, with tankers of identical types in terms of flag state and capacity. In response to EU oil sanctions, the firm can re-plan its shipping services in two ways. The first way is to switch the flag states of tankers that are not eligible to operate on a certain ship route. Here, note that we allow for a group of tankers to switch flag states to be eligible to serve multiple routes. The flag switching operation inevitably brings corresponding costs to the tanker shipping firm. We let c^{S}_{hr} represent an auxiliary parameter that equals zero if and only if tankers from group h can operate on route r under their current flag states without the need for flag switching, and equals the lowest flag switching cost (USD) of switching the tanker's flag state that is from group h to be eligible to operate on ship route r otherwise.

Another way to adapt to EU oil sanctions is to reposition tankers according to their flag states, which means moving eligible tankers (regardless of a qualified tanker whose current flag state is eligible or a qualified tanker after flag switching) from other groups to a ship route. In ship repositioning operations, the firm incurs costs, denoted by c^{R}_{hr}, which represent repositioning costs for moving a tanker from group h to route r. Based on the above two ways, an important decision in this integrated optimization problem, fleet repositioning, is introduced first. We let δ_{hr} represent the deployment of tankers from group h on route r. Obviously, the sum of tankers from group h across all routes ($\sum_{r \in R} \delta_{hr}$) cannot surpass the total number of tankers in group h, denoted by s_h. The deployment of tankers on a route also depends on the number of round trips these tankers complete during the planning period, which is the second decision denoted by γ_{hr}. Here, we note that the number of round trips of each route should meet or exceed the corresponding minimum frequency requirement which is influenced by the port's temporary storage capacity limits and defined as m_r.

The above round-trip completion planning and crude oil transportation scheduling, i.e., the amount of crude oil transported by a tanker each time, are also intertwined. We let β_{hr} denote the crude oil volume transported in one round trip by a tanker from group h on route r. It is obvious that the transported volume of each tanker cannot exceed the tanker's corresponding maximum transported volume which is defined as o_h, and during the planning period, tankers must meet the total crude oil transport demand for each route which is denoted by d_r. The last decision in this study is sailing speed optimization, and we let I_r represent the set of all legs (ports of call) on route r. Here, we note that only two legs, i.e., a laden lag and a ballast leg, are considered for each ship route. The speed (knot) of tankers sailing during leg i on route r, denoted by π_{ri}, should be within the feasible range of speed, i.e., $[\underline{v}, \overline{v}]$ where $\overline{v}$ and $\underline{v}$ are the maximum and minimum speeds, respectively.

The aim of this study is to help the tanker shipping firm minimize its overall costs, including costs related to flag switching, repositioning, and fuel. First, the sum of the flag switching cost and the repositioning cost can be calculated by $\sum_{r\in R}\sum_{h\in H}(c^{S}_{hr}\delta_{hr} + c^{R}_{hr}\delta_{hr})$. Calculating fuel costs is more complex. In addition to the sailing speed, the fuel consumption is affected by the tanker's displacement which refers to the total weight of the tanker itself, the amount of crude oil loaded, ballast water, and bunker [25,28,29]. We let b_h, f, and l_{ri} represent the total weight of the tanker itself, ballast water, and bunker of ships in group h (ton), the unit fuel price (USD/ton), and the length of leg i on route r (n mile), respectively. The total fuel cost is given by $\sum_{r\in R}\sum_{h\in H} f\gamma_{hr}[\dot{k}_{r,0}\pi_{r,0}^{\ddot{k}_{r,0}}(\beta_{hr}+b_h)^{\dddot{k}_{r,0}}\frac{l_{r,0}}{\pi_{r,0}} + \dot{k}_{r,1}\pi_{r,1}^{\ddot{k}_{r,1}}b_h^{\dddot{k}_{r,1}}\frac{l_{r,1}}{\pi_{r,1}}]$, where $\dot{k}_{r,i}$, $\ddot{k}_{r,i}$, and $\dddot{k}_{r,i}$ are coefficients that calculate the fuel consumption per hour for different legs. Here, we allow for a dynamic relationship among fuel consumption, speed, and load. Specifically, during the transportation of crude oil, the total weight of crude oil gradually decreases, which is because crude oil is consumed and converted into gas. Hence, the relationship among fuel consumption, speed, as well as load per hour is different for different legs. In summary, the objective is thus to minimize $\sum_{r\in R}\sum_{h\in H}[c^{S}_{hr}\delta_{hr} + c^{R}_{hr}\delta_{hr} + f\gamma_{hr}(\dot{k}_{r,0}\pi_{r,0}^{\ddot{k}_{r,0}}(\beta_{hr}+b_h)^{\dddot{k}_{r,0}}\frac{l_{r,0}}{\pi_{r,0}} + \dot{k}_{r,1}\pi_{r,1}^{\ddot{k}_{r,1}}b_h^{\dddot{k}_{r,1}}\frac{l_{r,1}}{\pi_{r,1}})]$.

3.2. Model Formulation

Based on the analysis presented earlier, this section introduces a nonlinear IP model. Before presenting the mathematical model, notation used in this model is listed as follows.

Indices and sets:

R	set of all routes, $r \in R$.
I_r	set of all legs (ports of call) on route r, $i \in I_r = \{0, 1\}$; $i = 0$, and $i = 1$ correspond to laden legs, and ballast legs, respectively.
H	set of all tanker groups, $h \in H$.
Z_+	set of all non-negative integers.

Parameters:

b_h	total weight of the tanker itself, bunker, and ballast water for tankers in group h (ton).
c^{R}_{hr}	repositioning cost of moving a tanker from group h to route r, which can be calculated by multiplying the operating cost by the repositioning time; the repositioning time includes the sailing time between the port where the tanker is currently located and the first port of call of the goal route r, plus an additional three days for preparation [30] (USD).

c_{hr}^{S}	auxiliary parameter; equals 0 if and only if tankers from group h are eligible to operate on route r under their current flag states without flag switching and equals the lowest flag switching cost (USD) of switching the flag state of a tanker from group h to be eligible to operate on ship route r otherwise.
d_r	total demand for crude oil transportation for route r over the planning period.
f	unit fuel price (USD/ton).
$\dot{k}_{r,i}, \ddot{k}_{r,i}, \dddot{k}_{r,i}$	coefficients to calculate the per-hour fuel consumption of a tanker while travelling.
l_{ri}	length of leg i on route r (n mile).
m_r	minimum frequency requirement for route r during the planning period, which is linked to the capacity limit of the port's temporary storage area.
n_{ri}	duration of a ship stays at port of call i on route r (hour).
o_h	maximum capacity of a tanker from group h.
s_h	number of tankers in group h.
t	length of the planning horizon (day).
$\underline{v}, \overline{v}$	minimum and maximum speeds of tankers, respectively (knot).

Decision Variables:

π_{ri}	integer; speed of tankers sailing during leg i on route r (knot).
β_{hr}	integer; transported volume of crude oil for a round trip by a tanker from group h on route r.
γ_{hr}	integer; number of round trips completed by tankers from group $h \in H$ on route r during the planning horizon.
δ_{hr}	integer; number of tankers from group $h \in H$ assigned to route r.

Mathematical model [M1]:

$$\min \sum_{r\in R} \sum_{h\in H} [c_{hr}^{S}\delta_{hr} + c_{hr}^{R}\delta_{hr} + f\gamma_{hr}(\dot{k}_{r,0}\pi_{r,0}{}^{\ddot{k}_{r,0}}(\beta_{hr}+b_h)^{\dddot{k}_{r,0}}\frac{l_{r,0}}{\pi_{r,0}} + \dot{k}_{r,1}\pi_{r,1}{}^{\ddot{k}_{r,1}} b_h{}^{\dddot{k}_{r,1}}\frac{l_{r,1}}{\pi_{r,1}})] \quad (1)$$

$$\text{subject to} \, \beta_{hr} \le o_h \forall h \in H, r \in R \quad (2)$$

$$\sum_{r\in R} \delta_{hr} \le s_h \ \ \forall h \in H \quad (3)$$

$$\sum_{h\in H} \beta_{hr}\gamma_{hr} \ge d_r \ \ \forall r \in R \quad (4)$$

$$\sum_{h\in H} \gamma_{hr} \ge m_r \ \ \forall r \in R \quad (5)$$

$$\gamma_{hr}\sum_{i\in I_r} (\frac{l_{ri}}{24\pi_{ri}} + \frac{n_{ri}}{24}) \le t\delta_{hr} \ \ \forall h \in H, r \in R \quad (6)$$

$$\underline{v} \le \pi_{ri} \le \overline{v} \ \ \forall r \in R, i \in I_r \quad (7)$$

$$\beta_{hr} \in Z_+, \ \ \delta_{hr} \in Z_+, \ \ \gamma_{hr} \in Z_+ \forall h \in H, r \in R \quad (8)$$

$$\pi_{ri} \in Z_+ \ \forall r \in R, i \in I_r. \quad (9)$$

Objective (1) minimizes the total cost, which includes the costs of flag switching, repositioning, and fuel consumption. Here, we notice that we allow for a group of tankers to be repositioned to serve multiple routes, and the value of δ_{hr} also equals the number of tankers from group h assigned to route r after flag switching if the value of c_{hr}^{S} is not zero. Constraints (2) ensure that the transported volume per round trip completed by each tanker cannot exceed the maximum volume of the tanker. Constraints (3) guarantee that the number of tankers from any group across all routes must not exceed the number of tankers available in that group. Constraints (4) require that the deployed tankers meet the crude oil transportation needs for each route during the planning period. Constraints (5) ensure that the total number of completed round trips cannot be less than the minimum frequency required for the route, which is influenced by the port's temporary storage capacity limits. Constraints (6) and (7) ensure appropriate total sailing times for all round trips in the planning period and feasible speeds for the deployed tankers. Constraints (8) and (9) define the ranges for the decision variables.

3.3. Linearization

Model [M1] has a nonlinear objective function (1) and nonlinear constraints (4) and (6). Hence, this study linearizes these nonlinear parts in this section.

Parameter:

Q_{hr}	maximum value of γ_{hr}, which equals $ts_h/\sum_{i\in I_r}(\frac{l_{ri}}{24\overline{v}}+\frac{n_{ri}}{24})$.

Variable:

ω_{hrpq}	binary; equals 1 if and only if values of β_{hr} and γ_{hr} are p and q, respectively; 0 otherwise.

Constraints:

$$\sum_{p\in\{0,\cdots,o_{hr}\}}\sum_{q\in\{0,\cdots,Q_{hr}\}}\omega_{hrpq}=1\ \ \forall h\in H, r\in R \tag{10}$$

$$\sum_{p\in\{0,\cdots,o_{hr}\}}\sum_{q\in\{0,\cdots,Q_{hr}\}}p\omega_{hrpq}=\beta_{hr}\ \ \forall h\in H, r\in R \tag{11}$$

$$\sum_{p\in\{0,\cdots,o_{hr}\}}\sum_{q\in\{0,\cdots,Q_{hr}\}}q\omega_{hrpq}=\gamma_{hr}\ \ \forall h\in H, r\in R \tag{12}$$

$$\omega_{hrpq}\in\{0,1\}\ \forall h\in H, r\in R, p\in\{0,\cdots,o_{hr}\}, q\in\{0,\cdots,Q_{hr}\}. \tag{13}$$

Then, Constraints (4) are replaced with the following constraints:

$$\sum_{h\in H}\sum_{p\in\{0,\cdots,o_{hr}\}}\sum_{q\in\{0,\cdots,Q_{hr}\}}pq\omega_{hrpq}\geq d_r\ \ \forall r\in R. \tag{14}$$

Next is the linearization process of Constraints (6).

Index and set:

V	set of all permissible speeds, $v\in V=\{\underline{v},\ \underline{v}+1,\ldots,\overline{v}-1,\ \overline{v}\}$.

Parameter:

M	big-M for linearization.

Variables:

α_{riv}	binary; equals 1 if and only if tanker's speed sailing on leg i of route r is v; 0 otherwise.
ε_{hriv}	integer; equals γ_{hr} if and only if tanker's speed sailing on leg i of route r is v; 0 otherwise.

Constraints:

$$\sum_{v\in V}\alpha_{riv}=1\ \ \forall r\in R, i\in I_r \tag{15}$$

$$\pi_{ri}=\sum_{v\in V}\alpha_{riv}v\ \ \forall r\in R, i\in I_r \tag{16}$$

$$\varepsilon_{hriv} \geq \gamma_{hr} + (\alpha_{riv} - 1)M \ \ \forall h \in H, r \in R, i \in I_r, v \in V \tag{17}$$

$$\varepsilon_{hriv} \leq \gamma_{hr} \ \ \forall h \in H, r \in R, i \in I_r, v \in V \tag{18}$$

$$\varepsilon_{hriv} \leq \alpha_{riv} M \ \ \forall h \in H, r \in R, i \in I_r, v \in V \tag{19}$$

$$\alpha_{riv} \in \{0,1\} \ \ \forall r \in R, i \in I_r, v \in V \tag{20}$$

$$\varepsilon_{hriv} \in Z_+ \ \ \forall h \in H, r \in R, i \in I_r, v \in V. \tag{21}$$

Then, Constraints (6) are replaced with the following constraints:

$$\sum\nolimits_{i \in I_r} \left(\frac{n_{ri}\gamma_{hr}}{24} + \sum\nolimits_{v \in V} \frac{l_{ri}\varepsilon_{hriv}}{24v}\right) \leq t\delta_{hr} \ \ \forall h \in H, r \in R. \tag{22}$$

Finally, the nonlinear part in Objective (1), i.e., $f\gamma_{hr}[\dot{k}_{r,0}\pi_{r,0}{}^{\ddot{k}_{r,0}}(\beta_{hr} + b_h)^{\dddot{k}_{r,0}} \frac{l_{r,0}}{\pi_{r,0}} + \dot{k}_{r,1}\pi_{r,1}{}^{\ddot{k}_{r,1}} b_h{}^{\dddot{k}_{r,1}} \frac{l_{r,1}}{\pi_{r,1}}]$, can be first transformed to $fl_{r,0}\dot{k}_{r,0}\gamma_{hr}\pi_{r,0}{}^{(\ddot{k}_{r,0}-1)}(\beta_{hr} + b_h)^{\dddot{k}_{r,0}} + fl_{r,1}\dot{k}_{r,1}\gamma_{hr}\pi_{r,1}{}^{(\ddot{k}_{r,1}-1)} b_h{}^{\dddot{k}_{r,1}}$, which can be further transformed to $f\sum_{p \in \{0,\cdots,o_{hr}\}} \sum_{q \in \{0,\cdots,Q_{hr}\}} \omega_{hrpq}[l_{r,0}\dot{k}_{r,0}q\pi_{r,0}{}^{(\ddot{k}_{r,0}-1)}(p + b_h)^{\dddot{k}_{r,0}} + l_{r,1}\dot{k}_{r,1}q\pi_{r,1}{}^{(\ddot{k}_{r,1}-1)} b_h{}^{\dddot{k}_{r,1}}]$ because of the existence of the newly defined variable ω_{hrpq}. Then, a new variable μ_{hrivpq} needs to be defined to substitute for the multiplication of variables π_{ri} and ω_{hrpq}, along with corresponding constraints.

Variable:

μ_{hrivpq}	binary; equals 1 if and only if values of both ω_{hrpq} and α_{riv} are 1; 0 otherwise.

Constraints:

$$\mu_{hrivpq} \geq \alpha_{riv} + \omega_{hrpq} - 1 \ \ \forall h \in H, r \in R, i \in I_r, v \in V, p \in \{0, \cdots, o_{hr}\}, q \in \{0, \cdots, Q_{hr}\} \tag{23}$$

$$\mu_{hrivpq} \leq \alpha_{riv} \ \ \forall h \in H, r \in R, i \in I_r, v \in V, p \in \{0, \cdots, o_{hr}\}, q \in \{0, \cdots, Q_{hr}\} \tag{24}$$

$$\mu_{hrivpq} \leq \omega_{hrpq} \ \ \forall h \in H, r \in R, i \in I_r, v \in V, p \in \{0, \cdots, o_{hr}\}, q \in \{0, \cdots, Q_{hr}\} \tag{25}$$

$$\mu_{hrivpq} \in \{0,1\} \ \ \forall h \in H, r \in R, i \in I_r, v \in V, p \in \{0, \cdots, o_{hr}\}, q \in \{0, \cdots, Q_{hr}\} \tag{26}$$

Consequently, Model [M1] is transformed into its linear version:

[M2]

$$\begin{aligned} \min \sum\nolimits_{r \in R} \sum\nolimits_{h \in H} [c^{S}_{hr}\delta_{hr} + c^{R}_{hr}\delta_{hr} + f\sum\nolimits_{p \in \{0,\cdots,o_{hr}\}} \sum_{q \in \{0,\cdots,Q_{hr}\}} \sum\nolimits_{v \in V} (l_{r,0}\dot{k}_{r,0}qv^{(\ddot{k}_{r,0}-1)}(p + b_h)^{\dddot{k}_{r,0}}\mu_{hr0vpq} \\ + l_{r,1}\dot{k}_{r,1}qv^{(\ddot{k}_{r,1}-1)} b_h{}^{\dddot{k}_{r,1}}\mu_{hr1vpq})] \end{aligned} \tag{27}$$

subject to Constraints (2), (3), (5), (7)–(26).

[M2] is a mixed-integer linear optimization model that can be solved by off-the-shelf linear optimization solvers.

4. Computational Experiments

To assess the proposed model's effectiveness, several numerical experiments are conducted on a laptop (Intel Core i7, 2.6 GHz; Memory, 16 G, Intel: Santa Clara, CA, USA). The mathematical model is executed in Gurobi 10.0.1 (Anaconda, Python 22.11.1). This section begins by introducing the parameter settings in Section 4.1, presents the experimental outcomes in Section 4.2, and concludes with sensitivity analyses in Section 4.3 to provide managerial insights.

4.1. Experimental Setting

In this study, there are six available tanker groups whose detail information is summarized in Table 1. Here, we note that Group 1, based at the Port of Saint Petersburg, has a total capacity of 750,000 tons, reflecting the high frequency and medium-distance voyages to ports in Northern Europe. The 15 tankers in this group correspond to the medium sizes typically used on these routes. Groups 2 and 3, both based at the Port of Jeddah, have capacities of 180,000 tons and 50,000 tons per tanker, respectively. These capacities cater to the long-haul journeys to Asian markets and shorter regional operations within the Middle East, requiring tankers of two sizes depending on the cargo volume. Group 4, based at the Port of Qingdao, has a total capacity of 3,750,000 tons. The large-scale crude oil import operations in China requires the use of larger tankers. Lastly, Groups 5 and 6 at the Port of Piraeus have capacities of 400,000 tons and 900,000 tons, respectively, aligning with Mediterranean trade patterns. These capacities reflect the use of smaller tankers for regional trade and larger tankers for extended routes to Western Europe. Moreover, due to EU oil sanctions, Greek-flagged tankers cannot be deployed on routes whose departure port is in Russia.

Table 1. Tanker group information summary.

Group ID	Number	Layup	Flag State	Total Tank Capacity (tons)
1	15	Port of Saint Petersburg (Russia)	Russia	750,000
2	10	Port of Jeddah (Saudi Arabia)	Saudi Arabia	1,800,000
3	10	Port of Jeddah (Saudi Arabia)	Saudi Arabia	500,000
4	15	Port of Qingdao (China)	China	3,750,000
5	5	Port of Piraeus (Greece)	Greece	400,000
6	5	Port of Piraeus (Greece)	Greece	900,000

Note: the term 'Layup' in the column refers to the initial location from which tankers start operating.

The planning horizon (i.e., t) is established as 60 days. Since this study is an extension of Ref. [27], some value settings in this study, including a seven-route crude oil transport network and values of parameters m_r, d_r, c^{R}_{hr}, o_h, l_{ri}, and daily operating costs of ships, are similar to those in Ref. [27]. For ships from group h allocated to route r, the flag switching cost (c^{S}_{hr}) is zero if the ship is eligible to operate on route r according to its current flag state, and set to USD 6500 if the ship is ineligible [31,32]. Values of $\underline{v}$ and $\overline{v}$ are 10 and 16 (knot), respectively [33]. Unit fuel price (f) is set to USD 767 per ton, based on the average price of very low sulfur fuel oil (VLSFO) across 20 major global ports from 20 May 2022 to 19 May 2023 which is 767 USD/ton [34]. The value of n_{ri} is randomly selected from $\{12, 24, 36\}$. Values of $\dot{k}_{r,0}$, $\ddot{k}_{r,0}$ and $\dddot{k}_{r,0}$ are set to 0.00022, 2.5506, and 0.2072, respectively; values of $\dot{k}_{r,1}$, $\ddot{k}_{r,1}$, and $\dddot{k}_{r,1}$ are set to 0.00021, 2.5505, and 0.2071, respectively.

4.2. Result Summary

The first set of numerical experiments contains 18 numerical instances, each characterized by the numbers of tanker groups ($|H|$) and routes ($|R|$). The results for these instances are presented in Table 2, showing the objective values in USD and the CPU time required for computation. The longest CPU computing time for the 18 computational instances is less than two hours. Based on this, we believe that the model can efficiently tackle real-world-sized problems, demonstrating its practicality and effectiveness.

Table 2. Results of 18 computational instances.

$\|H\|$	$\|R\|$	OBJ (USD)	CPU Time (s)
4	2	775,867.23	9
	2	859,839.13	9
	3	1,181,422.07	111
	3	1,212,194.02	198
	4	6,991,514.60	8
	4	6,464,678.51	10
	5	11,886,910.86	27
	5	11,432,950.08	12
6	3	1,212,194.02	9
	3	1,218,239.98	9
	4	5,816,731.73	9
	4	5,722,366.62	10
	5	10,920,457.19	110
	5	12,196,910.26	29
	6	16,293,825.93	476
	6	16,650,932.12	775
	7	20,149,230.14	4666
	7	21,000,171.05	4905

4.3. Sensitivity Analyses

In the previous numerical experiments, key parameters like unit fuel price, transportation demand, and repositioning cost are assumed to be constant. Recognizing that these parameters may vary in real-world scenarios, we perform three sensitivity analyses using a computational instance with 6 tanker groups ($|H|$) and 7 routes ($|R|$) to examine their impacts on operations management.

First, our analysis focuses on the effect of the unit fuel price (f) on operations management. Based on fuel price data provided in [34], the price range of VLSFO at 20 major ports worldwide varies between USD 581.18 and USD 1143.56 per ton from 20 May 2022 to 19 May 2023. Based on this, we set the fuel price range of f between USD 500 and USD 1200 per ton to assess its impact on operations management. Table 3 records the unit fuel price (USD/ton), the objective function value of the model (i.e., the total cost of the tanker firm), and tanker speeds during each leg. As illustrated in Table 3, we find that as the unit fuel price rises, the tanker firm reduces sailing speeds on two long-distance routes, each exceeding 20,000 nautical miles, to reduce fuel costs during voyages. This practice is corroborated by multiple existing studies, which demonstrate that slow steaming effectively reduces fuel costs, as shown in [35].

Table 3. Effect of the unit price of fuel on operations management.

f (USD/ton)	OBJ (USD)	Sailing Speed π_{ri} (knot)						
		r=1	r=2	r=3	r=4	r=5	r=6	r=7
500	15,925,970.26	[11, 13]	[10, 10]	[12, 13]	[13, 15]	[13, 16]	[11, 12]	[10, 10]
550	16,716,842.92	[11, 13]	[10, 10]	[12, 13]	[13, 15]	[13, 16]	[11, 12]	[10, 10]
600	17,507,715.56	[11, 13]	[10, 10]	[12, 13]	[13, 15]	[13, 16]	[11, 12]	[10, 10]
650	18,298,588.19	[11, 13]	[10, 10]	[12, 13]	[13, 15]	[13, 16]	[11, 12]	[10, 10]
700	19,089,460.82	[11, 13]	[10, 10]	[12, 13]	[13, 15]	[13, 16]	[11, 12]	[10, 10]
750	19,880,333.45	[11, 13]	[10, 10]	[12, 13]	[13, 15]	[13, 16]	[11, 12]	[10, 10]
800	20,671,206.08	[11, 13]	[10, 10]	[12, 13]	[13, 15]	[13, 16]	[11, 12]	[10, 10]
850	21,462,078.71	[11, 13]	[10, 10]	[12, 13]	[13, 15]	[13, 16]	[11, 12]	[10, 10]
900	22,252,951.34	[11, 13]	[10, 10]	[12, 13]	[13, 15]	[13, 16]	[11, 12]	[10, 10]

Table 3. *Cont.*

f (USD/ton)	OBJ (USD)	Sailing Speed π_{ri} (knot)						
		r=1	*r*=2	*r*=3	*r*=4	*r*=5	*r*=6	*r*=7
950	23,003,700.83	[11, 13]	[10, 10]	[12, 13]	[13, 15]	[12, 15]	[11, 12]	[10, 10]
1000	23,751,843.61	[11, 13]	[10, 10]	[12, 13]	[13, 15]	[12, 15]	[11, 12]	[10, 10]
1050	24,499,986.40	[11, 13]	[10, 10]	[12, 13]	[13, 15]	[12, 15]	[11, 12]	[10, 10]
1100	25,202,607.92	[11, 13]	[10, 10]	[12, 13]	[12, 14]	[11, 13]	[11, 12]	[10, 10]
1150	25,893,548.96	[11, 13]	[10, 10]	[12, 13]	[12, 14]	[11, 13]	[11, 12]	[10, 10]
1200	26,584,490.00	[11, 13]	[10, 10]	[12, 13]	[12, 14]	[11, 13]	[11, 12]	[10, 10]

Notes: (1) in the column 'Sailing speed π_{ri} (knot)', the two numbers in the brackets represent the sailing speeds during the first and second legs, respectively; (2) the information on port calls for the seven shipping routes is as follows: Route 1: Port of Jeddah–Port of Rotterdam–Port of Jeddah (via Suez canal route); Route 2: Port of Jeddah–Port of Piraeus–Port of Jeddah (via Suez canal route); Route 3: Port of Jeddah–Port of Algeciras–Port of Jeddah (via Suez canal route); Route 4: Port of Saint Petersburg–Port of Qingdao–Port of Saint Petersburg (via Suez canal route); Route 5: Port of Saint Petersburg–Port of Nagoya–Port of Saint Petersburg (via Suez canal route); Route 6: Port of Saint Petersburg–Port of Busan–Port of Saint Petersburg (via Suez canal route); Route 7: Port of Jeddah–Port of Qingdao–Port of Jeddah; (3) the distances for routes 1 to 7 are (in nautical miles) 8152, 2734, 5390, 24,054, 24,918, 24,126, and 13,596, according to the benchmark established by Ref. [36].

Second, the effect of total crude oil transportation demand (d_r) on operations management is explored. According to the analysis in Ref. [37], this demand in 2024 is expected to increase by 4.5% to 6.5% compared to 2022. To examine this change within the model while keeping other parameter values constant, we set the value of d_r to vary between 1.000 and 1.065 times. Table 4 presents the ratio of change in d_r, objective function value (OBJ, USD), and the data on several operations decisions, including the total volume transported in a round trip completed by all deployed tankers ($\sum_{r\in R}\sum_{h\in H}\beta_{hr}$), the number of deployed tankers ($\sum_{r\in R}\sum_{h\in H_r}\delta_{hr}$), the number of round trips ($\sum_{r\in R}\sum_{h\in H_r}\gamma_{hr}$), and sailing speeds during each voyage leg (π_{ri}, knot). As shown in Table 4, crude oil transportation demand has a crucial impact on the operations decisions of tanker shipping firms. It directly affects the companies' crude oil transportation plans, tanker deployment, and the sailing speed plans of tankers. Specifically, the tanker shipping firm can respond to the increased transportation demand by deploying larger-capacity tankers or by increasing transportation frequency. At the same time, to minimize the cost increases that arise from these two strategies, the tanker shipping firm adopts slow steaming practices to reduce fuel costs.

Table 4. Effect of the total crude oil transport demand on operations management.

The Ratio of Change in d_r	OBJ (USD)	β (K)	δ	γ	π_{ri} (knot)
1.000	20,149,230.14	297	60	56	[11, 13, 10, 10, 12, 13, 13, 15, 13, 16, 11, 12, 10, 10]
1.005	20,582,425.60	321	60	56	[11, 13, 10, 10, 12, 13, 13, 15, 12, 15, 11, 12, 10, 10]
1.010	20,856,093.58	301	59	55	[11, 13, 10, 10, 12, 13, 13, 15, 13, 16, 12, 14, 10, 10]
1.015	20,856,093.58	301	59	55	[11, 13, 10, 10, 12, 13, 13, 15, 13, 16, 12, 14, 10, 10]
1.020	21,234,103.88	331	60	57	[11, 13, 10, 10, 12, 13, 12, 14, 12, 15, 12, 14, 10, 10]
1.025	21,363,646.59	307	60	55	[11, 13, 10, 10, 12, 13, 13, 15, 13, 16, 12, 14, 10, 10]
1.030	21,827,827.87	308	60	58	[11, 13, 10, 10, 12, 13, 13, 15, 13, 16, 12, 14, 10, 10]
1.035	21,832,606.40	312	60	58	[11, 13, 10, 10, 12, 13, 13, 15, 13, 16, 12, 14, 10, 10]
1.040	22,653,299.15	319	60	57	[11, 13, 10, 10, 12, 13, 13, 15, 12, 15, 12, 14, 12, 16]
1.045	22,679,605.27	313	60	58	[11, 13, 10, 10, 12, 13, 13, 15, 12, 15, 12, 14, 12, 16]
1.050	22,772,635.54	315	60	58	[11, 13, 10, 10, 12, 13, 13, 15, 12, 15, 11, 12, 12, 16]
1.055	22,852,197.46	316	60	59	[11, 13, 10, 10, 12, 13, 12, 14, 13, 16, 11, 12, 12, 16]
1.060	23,184,281.69	322	60	62	[11, 13, 10, 10, 12, 13, 12, 14, 13, 16, 11, 12, 10, 10]
1.065	23,534,471.22	317	60	61	[11, 13, 10, 10, 12, 13, 12, 14, 13, 16, 12, 14, 12, 16]

Notes: (1) columns β, δ, and γ represent the total volume transported in a round trip completed by all deployed tankers, the number of deployed tankers, and the number of round trips, respectively; (2) K represents thousands; (3) in the column 'π_{ri} (knot)', the 14 numbers in the brackets represent the sailing speed of the tanker during the first and second legs on routes 1 to 7, respectively.

Finally, we examine the effect of ship repositioning costs (c_{hr}^{R}) on operations management. To this end, different c_{hr}^{R} values are applied based on the repositioning time and tanker operating costs. According to data released in Ref. [38], from 2020 to 2021, operating costs for Small, Handys, Aframax, and Panamax tankers increased by 3% to 6%. Therefore, we set the value of c_{hr}^{R} to vary between 0.98 and 1.06 times its original value. As illustrated in Figure 1, where the x-axis shows the ratio of change in c_{hr}^{R} and the y-axis shows the total cost of the tanker shipping firm, i.e., OBJ (USD), we find that in this case, adjustments in repositioning cost linearly affect the total cost without altering other management decisions. The strict linearity observed in the relationship between the ratio of change in c_{hr}^{R} and the objective value in our study is because in our experimental setup, the change in the repositioning cost does not affect the values of other decision variables. Consequently, changes in the repositioning cost within this range only influence the total repositioning cost of the tanker shipping firm, resulting in a perfectly straight regression line across all points.

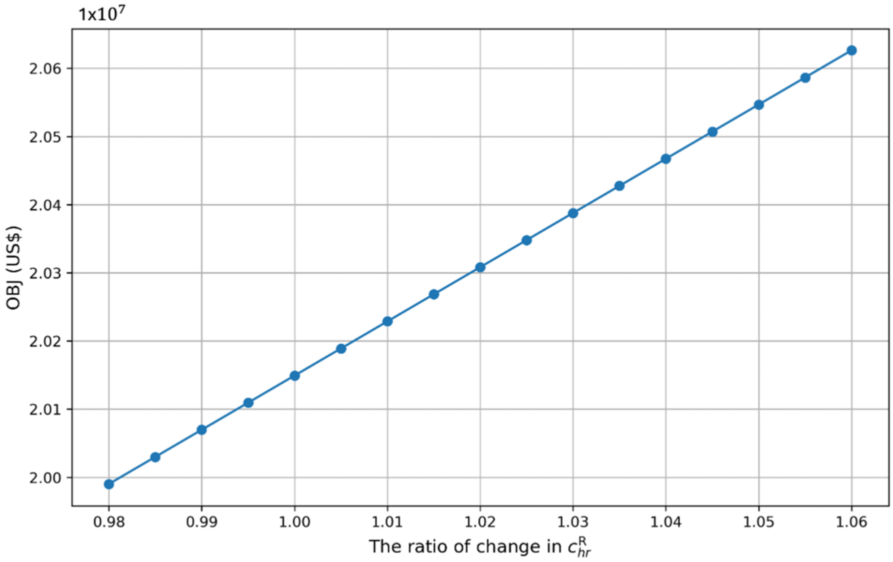

Figure 1. Effect of the repositioning cost on operations management.

5. Conclusions

This study extends the work in [27] by proposing two strategies to assist tanker shipping firms in complying with EU oil sanctions, with the aim of helping them reduce operating costs. The first strategy involves switching the flag states of tankers that are not eligible to operate on certain routes; the second strategy involves repositioning tankers based on their flag states. In summary, this study makes the following two contributions:

(1) We formulate a nonlinear IP model to assist tanker shipping firms in making optimal decisions regarding fleet repositioning, flag switching, crude oil transportation scheduling, and speed optimization. The longest solution time for the 18 computational instances is less than two hours, demonstrating that our proposed model is not only capable of effectively addressing such problems, but also shows significant potential in solving practical application issues. From a practical operational perspective, our model provides tanker shipping firms with the necessary tools to optimize their strategies, adapting to evolving regulations through strategic flag switching and fleet repositioning. This optimization not only reduces operational time but also reduces costs through more efficient scheduling. As for the short-term benefits, the application of this model enables firms to swiftly adapt to policy changes, thereby reducing the risk of fines or losses due to non-compliance. In the longer term, the strategies offered by our model may progressively enhance the efficiency and effectiveness of crude oil transportation services.

(2) Sensitivity analyses exploring how parameters including unit fuel price, crude oil transportation demand, and tanker repositioning costs impact operations decisions are performed to gain managerial insights. These insights reveal that slow steaming is the optimal response for tanker shipping firms when faced with rising unit fuel prices. Changes in transportation demand play a key role in operations management, directly affecting tanker repositioning, flag switching, transportation scheduling, and sailing speed decisions. Finally, the costs associated with tanker repositioning have a negligible impact on the operations management of tanker shipping firms, similar to the findings in [27].

Although this study makes certain contributions, there remains scope for further expansion. First, this study does not consider uncertain factors, especially uncertain fuel prices. Given that fuel costs constitute a significant portion of the total operating cost, future research could consider exploring the uncertainty in fuel prices. Second, the fluctuations in demand for crude oil transportation are quite noticeable. Considering the importance of steady crude oil transportation for the stability of the global economy, exploring how to build a robust crude oil transportation system is especially critical. This topic deserves detailed study.

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