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ABSTRACT

Container ships carry most of the world's cargo volume. Hence, Maritime transportation forms the backbone of the world merchandise trade. Today, with the advancement of shipbuilding technology and the increasing frequency of maritime transport, determining the optimal route for container ships has become more and more important for shipping lines and port managers. Accordingly, in the present study, we intend to investigate the ship routing problem using a mixed integer linear mathematical programming model. In order to solve the proposed model, we have used the meta-heuristic algorithms of differential evolution and gray wolf optimization in MATLAB software. In the end, it was shown that the proposed mathematical model and solution approaches can assist ship operators and terminal managers in making reasonable optimization decisions.

Keywords: Ship Routing Problem, Maritime Transportation, Container Ships, Port Time Windows, Gray Wolf Optimization (GWO), Differential Evolution (DE)

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1. INTRODUCTION

International trade largely depends on maritime transportation since ships are the most cost-effective means of transportation of a large volume of goods in long distances. Container ship routing has been one of the most important issues of transport companies and shipping lines, since, as mentioned, a significant volume of transportation includes sea transportation. In general, there are three types of maritime transportation (ship routing problem), which are presented below.

1) **Industrial transportation:** this type of transportation aims to minimize product transfer costs, and is often used to transfer petroleum and minerals. It is notable that the owner of the ship and the cargo is one person.
2) **Irregular transportation:** this type of transportation occurs with the goal of maximizing profits with no special rules and preset time. In addition, different ports are visited and their demands are met.
3) **Regular transportation:** in this type of transportation, which includes container ships, the goal is to maximize profits, in a way that the ship visits different ports in fixed routes at the same time intervals, and loading and unloading are carried out in each port. Regular transportation shipping companies provide services in the form of long-term, short-term, and spot contracts.

It is notable that the current research focused on regular transportation. The ship routing problem has been assessed in many studies, most of which can be considered as specific applications of the vehicle routing problem, where cargo is transferred between several loading and unloading ports. One of the most comprehensive studies in this area was conducted by Christiansen *et al*. in 2004 and 2013 (Christiansen *et al.*, 2013). Moreover, while there are uncertainties in maritime transportation, the majority of studies in this field have evaluated the ship routing problem in a definitive environment. There are some interesting exceptions in ship routing and planning in studies performed by Iswanto (2019) and Kisialiou *et al*. (2019). In fact, these researchers focused on the topic of uncertain demand and changing climatic conditions at oil and gas platforms (Kisialiou *et al.*, 2018, 2019). Korsvik and Fagerholt (2012) and Kosmas and Vlachos (2012) considered irregular ship routing problems along with other important decisions. Moreover, they developed several heuristic approaches to solve the proposed problem (Korsvik *et al.*, 2010; Kosmas and Vlachos, 2012). Norstad *et al.* (2011) assessed the topic of ship speed and route optimization in an integrated manner (Wang *et al.*, 2019). The foregoing research was expanded in 2019 by Wang *et al.*, who evaluated the effects of measures taken to decrease pollutant emission on operational decisions of transportation companies, as well as their environmental and economic outcomes (Wu *et al.*, 2021). Both of these studies applied the local search heuristic method with several start points. Wu *et al*. (2021) evaluated bulk carrier routing by selecting batched cargo. These scholars presented a combined problem of three sub-problems in irregular transportation (irregular ship routing problem) including: 1) fleet adjustment, 2) batched cargo selection, and 3) ship routing. In the end, a tailored branch-and-price-and-cut algorithm was developed to solve the compact mixed-integer linear programming formulation. According to the results, the robust algorithm of the research led to the production of optimal or near-optimal solutions in a short computational time (logical) for real samples (Brønmo *et al.*, 2010).

Brønmo *et al.* (2010) applied the "column generation algorithm" to solve the ship routing problem with flexible cargo sizes. In the end, the algorithm had a better performance, compared to the method in which all columns are generated from the beginning (Meng *et al.*, 2015). Stålhane *et al.* (2012) proposed a branch-price-and-cut method to solve a ship routing problem, where cargos were picked up and delivered (Hwang *et al.*, 2008). Meng *et al.* (2015) solved the fuel and ship routing problem using a branch-and-price (B&P) approach (Homsi *et al.*, 2020). Considering an unstable maritime market, Hwang *et al.* (2008) proposed a ship routing problem, in which profit difference was minimized. The model was solved using the B&P method (Tirado *et al.*, 2013). Homsi *et al.* (2020) proposed an exact B&P algorithm to solve the ship routing problem. These scholars presented a set of acceleration techniques to optimize the algorithm. In the end, algorithm performance was tested using a set of small data, the results of which demonstrated the algorithm's ability to solve larger-scale samples (Halvorsen-Weare *et al.*, 2013).

Most studies in the field of ship routing have focused on definitive parameter tuning, a small number of authors and researchers have taken uncertainty into account. An example is a research by Hwang *et al.* (2008), who considered uncertainties in revenue from renting ships and transporting instant market cargo. They aimed to maximize the expected revenue of a shipping company under defined profit variance limits (Tirado *et al.*, 2013). Tirado *et al.* (2013) addressed a dynamic ship routing problem, in which new cargos were randomly entered into the decision-making space. They adopted three heuristics to solve their proposed model (Agra *et al.*, 2013). Halvorsen *et al.* (2013) investigated a ship routing and scheduling problem in liquefied natural gas (LNG) industry. In their proposed problem, LNG was transported from a single producer to a set of customers over a period of time (planning horizon). In this study, the researchers took uncertainties in travel time and the rate of daily LNG generation into account. They developed a simulation-optimization framework to solve the proposed model and presented several approaches to improve the results at the end (Huang and Han, 2021). Agra *et al.* (2013) considered uncertainty in travel time in a ship routing problem. In the end, a robust column-and-row generation optimization algorithm was introduced (Liu *et al.*, 2020). Huang and Han (2021) optimized the route of containers in urban areas. They proposed a multi-objective mathematical model and ranked its solutions by the Topsis method (Li *et al.*, 2020). Liu *et al.* (2020) scheduled the train route using an optimization mathematical model. They divided demand into several sections using a variable neighborhood search algorithm (Zorarpacı and Özel, 2016).

Today, the efficient solving of many hybrid optimization problems known as NP-hard problems is one of the main challenges of mathematicians, scientists, and engineers. In the present study, we aimed to evaluate one of these problems known as the container ship routing problem while assuming certain time windows and demands of destination porters. In the ship routing problem, the main focus was on scheduling and routing a fixed fleet of ships in order to transport a set of cargoes under certainty. Another innovation of the present study was using novel meta-heuristic methods (differential evolution and grey wolf algorithms) to solve the container ship routing problem. The remainder of the study is described as follows: section 2 presents the research problem, as well as the necessary definitions and assumptions related to the ship routing problem. Section 3 expresses the final mathematical model and symbols, and section 4 introduces the differential evolution and grey wolf algorithms. Section 5 shows the numerical results and model implementation using the mentioned algorithms, and section 5 concludes. Moreover, approaches are proposed for future studies in section 6.

2. STATEMENT OF THE PROBLEM AND KEY DEFINITIONS

It is better for the customers of a container terminal to minimize the returned time. In other words, the waiting time is minimized and container loading and unloading are carried out as fast as possible to save on terminal costs. To reduce the time spent on container ships, terminal officials place particular emphasis on allocating resources and docks to ships. In the maritime industry, container terminal managers know that customers will seek another port if they are dissatisfied with port performance. Therefore, many of them tend to decrease (minimize) the returned time of ships with the existing resources (incurring the lowest costs) (Wu *et al.*, 2021). The following are definitions of the three essential terms used in this study:

- **Ship routing problem:** is one of the most important elements in the assessment of the performance of a shipping company. Finding the best route is one of the important issues in maritime transportation. However, the most suitable route is not necessarily the shortest route in this industry, and several other factors, including fuel consumption, demand of destination ports, and safety, are taken into account in decision-making with different degrees of importance.
- **Main port:** are ports that are on the international routes of container ships (intercontinental), and large container ships travel there with a large container volume. Main ports must have suitable equipment, draft, geographical location, and communication lines in order to attract customer satisfaction.
- **Loading capacity of a ship:** the difference between the amount of heavy handling and the amount of light handling is called cargo carrying capacity. The unit of container transport volume is TEU and represents a 20-foot container.

Ship routing includes ship distribution with several goods that cannot be integrated and combined. In addition, the cost and time of travel or transportation of cargo are different in routing for the distribution of ships with different capacities. The ships are also different in terms of number and type of compartments. It means that each compartment can be loaded with a certain type of goods, but only one type of product is loaded and delivered each time. The ship can pass several ports and even the start port on the route of transportation and delivery of cargo. However, it is assumed that all goods are unloaded by the end of travel, and the only ship with empty compartments is returned to start ports. Therefore, it could be said that when a ship's compartment is loaded with different goods, it will not lead to higher cost or longer time. Each port can load a large number of goods through the distribution of ships. It could be mentioned that each product has a limited supply level. In addition, each demand route receives and uses certain goods. Each product has an average level of daily consumption. Goods must be stored separately in port warehouses based on their specific conditions and characteristics. These warehouses have a maximum capacity. A group of ships sails between ports to ensure that there is sufficient warehouse capacity. A ship may load one or several goods from supply warehouses and unload them in a demand point or port. The present study determined the exact number of companies that arrived at a port and the number of loading and unloading. It is notable that loading and unloading are collectively specified. It is assumed that more than one ship can berth at a port simultaneously. In addition, several ships can load or unload different goods at the same time. However, a ship cannot simultaneously load and unload different goods. Waiting time is also allowed at the port. In supply ports, a ship may start its travel with delay due to the high volume of products. However, the time to reach the destination ports must be taken into account in this delay so that cargo deficit should not occur in these ports. In demand points (destination), the ship can wait until there is room in the warehouse for further unloading. The equipment and items in the ship's compartment are identified at the beginning of scheduling and routing. A ship's compartments may be empty, or there may be one or more goods in the compartment. The location of a ship is in the port or a point in the sea. In this problem, we deal with short-term and long-term operational planning and design. The number of ships and their overall capacity is considered to be fixed and specified for loading at ports during the planned period. Therefore, we overlooked the fixed cost of ships, such as the cost of renting and investment since the products in the production and consumption warehouses were owned by a single company. In this case, we only focused on the transportation cost and ship movement. Moreover, a total of 100 kilogallons per nautical mile of fuel was considered for all ships. Distances between ports are also calculated from a uniform distribution of between 10 and 200 nautical miles. Based on the mentioned conditions, we must determine the capacity of each ship and its primary location, the number of products that must be loaded or unloaded at each port, and the time window related to each port. The purpose of the problem is to determine the route for each ship so that the maximum volume of goods is moved with a minimum travel distance and to choose a route that has all the optimal conditions mentioned above (e.g., safety) or the majority of effective factors. In this study, however, we only considered destination port demand, ship capacity, and time window.

3. MATHEMATICAL MODELING

In this study, we proposed an optimization mathematical model to minimize the total variable shipping costs, including travel costs (fuel + personnel), toll fees, and port tariffs, while taking the limitations of delivery, carrying capacity, and time windows into account. The elements of the model are presented below:

$$Total\ Cost = Min \sum_{i=1}^{p} \sum_{j=1, i \neq j}^{p} \sum_{k=1}^{v} \sum_{\phi=1}^{\phi_{max}} \left(d_{ij} c_k x_{ijk\phi} + x_{ijk\phi} f_{ik} \right) \quad (1)$$

Subject to:

$$\sum_{i=1}^{p-1} x_{ilk\phi} - \sum_{j=2}^{p} x_{ljk\phi} = 0 \qquad \forall k \in V, \forall \phi \in \quad (2)$$

$$s_{ik\phi} + t_{ik\phi} + d_{ij} \times vel_k - s_{jk\phi} \le M(1 - x_{ijk\phi}) \quad \forall i, j \in P, i \neq j, \quad \forall k \in V, \forall \phi \in \Phi \quad (3)$$

$$s_{ik\phi} \gamma_{(i-1)k\phi\alpha} \le \alpha_\alpha \qquad \forall i \in P, i \neq j,\ \forall k \in V,\ \forall \phi \in \Phi,\ \forall \alpha \in C \quad (4)$$

$$\sum_{\alpha}^{\alpha_{max}} q_\alpha \gamma_{ik\phi\alpha} \le Q_k \qquad \forall k \in V,\ \forall \phi \in \Phi,\ \forall i \in P \quad (5)$$

$$\sum_{k=1}^{k_{max}} \gamma_{ik\phi\alpha} = 1 \qquad \exists i \in P,\ \exists \phi \in \Phi,\ \forall \alpha \in C \quad (6)$$

$$\sum_{i=1}^{p} \gamma_{ik\phi\alpha} x_{ijk\phi} \ge 1 \quad j = e_\alpha,\ \forall k \in V,\ \forall \phi \in \Phi,\ \forall \alpha \in C \quad (7)$$

$$Start_i \le s_{ik\phi} \le Finish_i \quad \forall k \in V,\ \forall \phi \in \Phi,\ \forall i \in P \quad (8)$$

The input variables used in the above formula were:

$G(P, A)$	A directed graph
$P = \{1, \ldots, p\}$	Set of nodes of graph G, where nodes 1-p represent ports.
$A = \{(i, j): i, j \in P, i \neq j\}$	Set of edges of graph G, which connect the i-th node to the j-th node and show the travel made by the ship from the i-th node to the j-th node.
$V = \{1, \ldots, k_{max}\}$	The total number of ships that may be used.
$C = \{1, \ldots, \alpha_{max}\}$	The total number of containers that must be transferred by ships.
$\Phi = \{1, \ldots, \phi_{max}\}$	Total travels (ϕ) for each ship show the number of arcs (I, j) that are traveled by a ship in a route.

Now, for each $i, j \in P : i \neq j$, $k \in V$, $\phi \in \Phi$, and $\alpha \in C$, we have:

d_{ij} Length of the edge (I, j) corresponding to the distance from the i-th port to the j-th port in nautical miles
vel_k Ship velocity (knot)
Q_k The capacity of the k-th ship
a_α Time of receiving the a-th container
o_α, e_α The origin and destination ports of the a-th container
f_{ik} Tariffs of the i-th port for the k-th ship
b_i Loading or unloading time of each container at the i-th port
c_k Travel costs (fuel consumption in kilogallon) for the k-th ship in dollars per nautical mile
$s_{ik\phi}$ When the k-th ship arrives at the ϕ-th port in the i-th travel
$Start_i$ Work start time of the i-th port
$Finish_i$ Work finish time of the i-th port
M A large fixed number

The model has two binary decision-making variables and seven constraints, as follows:

$x_{ijk\phi}$: 1, if the k-th ship travels from the i-th port to the j-th port in the i-th travel; otherwise, 0.
$\gamma_{ik\phi\alpha}$: 1, if the k-th ship loads the a-th container after leaving the i-th port in the ϕ-th travel.

Constraints 1: ensure that the ship will leave any

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