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Research paper

A strategic fleet size and mix vehicle routing model to analyse the impact of demand fluctuation on river-sea liner shipping

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ABSTRACT

The paper proposes a fleet size and mix vehicle routing model to optimize the river-sea liner shipping service. A mixed integer linear programming model is adopted as a rapid screening tool for strategic fleet planning to determine the type and number of river-sea vessels to deal with the fluctuation of the demand over the year, guaranteeing the efficiency and effectiveness of the shipping service. Moreover, the model provides a better-informed decision on the logistic infrastructure design, demand allocation and fleet size and composition in scenarios of demand uncertainty. Thus, the quantified decision support model increases the service level of the shipping service, reducing the frequent mismatches between fleet capacity and demand. A verification step aiming to test the behaviour of the model solution in a realistic case study is presented to analyse the impact of the demand fluctuation on the fleet composition.

In conclusion, river-sea vessels enable door-to-door transport via coastal and inland waterways without transhipment. This approach offers a reliable and cost-effective solution. The findings of the work may enhance the state of the art, expanding the narrow studies on river-sea liner shipping services and demonstrating the advantages of river-sea vessels.

Fleet Size and Mix Vehicle Routing Model (MILP)	
Sets:	
I	Set of vertexes *i,j* in the network;
V	Numbers of vessel *v* per model (*vehicle*);
M	Set of vessel's model *m*;
T	Time units (day);
Subscripts:	
i,j	vertex index;
v	vessel index;
m	vessel' model index;
t	time index;
Binary Variables:	
$x_{tijmv} \in \{0,1\}$	Decision to assign the vehicle *v*, of model *m*, to travel between vertexes *i,j*;
Continuous Variables:	
$y_{tij} \in Z$	Flow of cargo between vertexes *i,j*;
$t_{tmv} \in IR^{+}$	Number of travels performed per vessel *v* of model's type *m* per day *t*;
$n_{tmv} \in IR^{+}$	Number of vessels *v* of model's type *m* per day *t* needed to accomplish the routes;
$fleet_{tm} \in Z$	Fleet size of each vessel's model *m* per day *t*
$final_{m} \in Z$	Final fleet of each vessel's model *m*
$u_{tij} \in N_0^{+}$	Integer variable assigned to each customer *i* per day *t*

(*continued on next column*)

(*continued*)

Discrete Parameters:	
$DIST_{ij}$	Distance between vertexes (*i,j*)
$DEMAND_{ti}$	cargo demand per vertexes *i* per day *t*
$CAPACITY_{mv}$	Capacity of the vessel *v* of model *m*
$SPEED_{m}$	Speed of the model *m*
EXTT	Additional time of vessel's loading and unloading cargo.
RC_{m}	Rental cost of model *m*
VC_{m}	Variable cost of model *m*
$MAXN_{tmv}$	Maximum number of travels from loading port to unloading port per day *t*
MAXVERTEX	Number of total customers *i*

1. Introduction

1.1. Problem description

A new bauxite supply chain from West Africa to China has been growing during the last few years (Sanoh et al., 2022; Sun et al., 2023). The Chinese manufacturing industry has been increasing with the

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development of the global shipping markets (Gu and Liu, 2022), and Guinea has been considered one of the worldwide bauxite reserves with high quality, accounting for 30% of the global production (Wilhelm and Maconachie, 2021). According to Liu and Dong (2019), China is one of the world's largest bauxite importers. The authors highlighted that before 2014, China's trading partners were mainly Indonesia and Australia. However, since Indonesia announced that it will not export bauxite as raw materials, the authors also forecasted that China would search for other bauxite resources. Thus, Sanoh et al. (2022) identified that since 2015, the percentage of bauxite produced in Guinea and exported to China rose from 2% to 58% in 2020, in 2019, the peak of exportation (67%). The port of Yantai has been confirmed as China's leader in bauxite loading and unloading and has become a hub for ore transport (35°Nord, 2019). The recent maritime supply chain originates in Guinea, Noniz River, and may ends at Binzhou, Taoer River, via transhipment at the Yantai port (Fig. 1). The end customer leg of this supply chain is made with the river-sea bulk carrier ship.

Since the bauxite has a characteristic of easy fluidisation, the efficiency and effectiveness of the river-sea leg are required to not only minimise the cost and maximise the resources but also keep the demand of the end customer satisfied, which can be achieved by planning the appropriate number of vehicles in the fleet that can maintain the service level of the shipping transportation. An increasing number of studies have addressed the fleet planning problem (Hermeto et al., 2014; Hoff et al., 2010; Silva and Guedes Soares, 2014, 2017). Thus, most maritime fleet-size planning studies are designed to examine sea transportation as a liner or tramp service and industrial service to accomplish established tasks, e.g., offshore supply demand and maintenance logistics. Still, few papers have looked at fleet-size planning for river or river-sea transport. Pantuso et al. (2014) present a complete review of the maritime fleet planning problem, which can supplement these observations.

The river-sea transport is an excellent intermodal door-to-door transport because a single vessel can sail both coastal and inland waters (Charles, 2008). These vessels usually have shallower drafts and are wider than sea-going vessels, which still allows them to have acceptable motions when subjected to waves (Wang et al., 2018, 2020). The utilisation is limited by the cargo capacity and navigational conditions at sea and river waterways (Radmilović et al., 2011). Therefore, the fleet planning of the river-sea vessels has the characteristic of searching for heterogeneous vessels that can accomplish the fluctuation of the demand, allowing a full payload voyage. The present study aims to develop a mathematical model to support the decision makers during the strategic planning phase of determining the fleet of a river-sea vessel to guarantee the efficiency and effectiveness of the bauxite transportation from the transhipment port to the end customer.

The present work attempts to contribute to the research literature by considering the following issues:

1. Proposing a strategic plan for a fleet of river-sea vessels in liner service shipping, which involves determining the size and type of fleet, accounting for the fluctuating and seasonal demand to satisfy the end customer.
2. Integrating the fleet size and mix model with the vehicle routing model aiming at guaranteeing that the respective vessels in the fleet can accomplish the route requirements.
3. Enabling a better-informed decision when designing the logistic infrastructure, as well as the demand allocation and fleet size and composition, in a scenario of demand uncertainty.

Section 2 presents the literature review, and Section 3 describes the material and methods, including a better description of the river-sea transport and strategic planning of fleet size and mix problem. It also presents the mathematical model and assumptions. Section 4 addresses the steps of the solution construction, and the verification of the solution found, while Sections 5 and 6 discuss the solution results and the paper's main conclusions, respectively.

2. Literature review

Maritime transportation forms the back-bone of the world merchandise trade (Wu et al., 2021), and three types of maritime services can be performed: industrial, tramp and liner shipping. The former service adopts fixed routes to regular ports following a schedule. Thus, the tramp service does not present regular shipments, and the industrial service performs regular and irregular routes to deliver and pick up personnel, products, parts, or equipment. However, shipping companies may operate simultaneously in different shipping modes, which makes it difficult to distinguish between these shipping services (Fagerholt et al., 2010). Therefore, fleet planning is a common problem of these services, impacting cargo demand varying during a determined period. Nowadays, the planning fleet problem also attempts to increase the operational efficiency in terms of carbon intensity indicator (CII) (Yuan et al., 2023). Therefore, defining the number of vessels designed to accomplish the specified routes is crucial to reducing shipping costs.

The fleet planning problem falls as an extension of the vehicle routing problem (VRP), which is a well-studied topic of the logistic transportation sector (Silva et al., 2023) and is named the fleet size and mix problem (FSMP). This problem searches for the minimum cost of a fleet of vessels to accomplish the routes during a single period in the planning horizon. A simple variation of this problem is the composition of a homogenous fleet, named fleet size problem (FSP) (Pantuso et al., 2014). Thus, an extension of the FSPM, is the fleet renewal problem (FRP), where the main goal is dynamically adjusting the fleet from time to time, also referred to as a multi-period FSMP.

Even being an extension of the VRP problem, scarce literature regarding strategic fleet size planning is still present nowadays. A complete review of fleet composition is presented by Hoff et al. (2010). Also, Pantuso et al. (2014) present a survey of maritime cases. Hoff et al. (2010) discussed the relevant papers and the most important industrial aspects of the fleet composition problem as well as the diverse set of vehicle types adopted in real cases, the different tasks that are accomplished by the vehicles, the strategic planning decisions and the impact of ship and road-based transportation on routing problems. Thus, the maritime cases of fleet size and mix problem are presented by Pantuso et al. (2014), highlighting the call for more accurate decision support models in maritime transportation to integrate the fluctuations in the shipping market and the frequent mismatches between fleet capacities and demands.

The industry service commonly appearing in the offshore oil industry is the supply vessel planning problem (SVP), which consists of searching

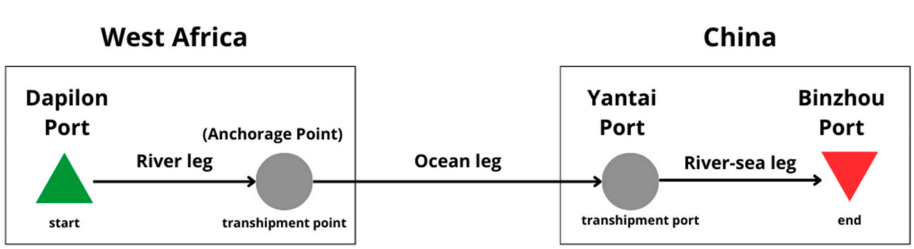

Fig. 1. Bauxite imports supply chain from West Africa to the end customer in China.

for the optimal fleet of supply vessels and the corresponding weekly voyages and schedules. In this regard, Halvorsen-Weare and Fagerholt (2011) combined simulation and mathematical modelling to define robust solutions to find voyages and schedules allowing for unforeseen events. Santos et al. (2023, 2022) developed stochastic programming models to handle the operation with uncertainties. The former only considers the uncertainties in demand whereas the latter considers demand and weather conditions.

Moreover, new challenges are arriving in the offshore wind industry, moving from onshore to offshore development in coastal and shallow waters. Accordingly, new logistics for wind turbine maintenance are becoming relevant, which consists of determining the fleet size, routing, and schedule for the service operational vessels to perform the predictive and corrective maintenance at offshore wind farms. Silva et al. (2023) developed two mathematical models to look for the optimal location of offshore bases and routing of the service operational vessels and determine the optimal fleet composition. Tusar and Sarker. (2023) developed a fleet size and mix model to establish the best vessel assignments to the routes and technicians on the vessels at a minimal cost. The model's main advantage is that it considers real-life peculiarities and limits of the vessel management of offshore wind farms. Sperstad et al. (2017) investigate the uncertainty regarding input data and modelling assumptions. Moreover, the uncertainties in economic aspects and operational processes, as well as failure occurrence, demand and weather conditions are accomplished by Halvorsen-Weare et al. (2013), Gundegjerde et al. (2015), Stålhane et al. (2019).

For the tramp service, Zeng and Yang (2005) developed a Two-phase Tabu Search algorithm attempting to determine the fleet size and routing problem; Fagerholt et al. (2010) provide a combination of simulation and optimisation that can be applied to a wide range of strategic decisions as well as fleet size and contract analyses. Wu et al. (2021) presented a robust solution methodology – mixed integer linear programming, a set covering model and a branch-and-price-and-cut algorithm – to solve the fleet adjustment, cargo selection and ship routing problems. Schwartz (1968) developed a discrete programming model to define a fleet of barges for the movement of a corresponding selected cargo over a particular river segment.

However, the works of Lane et al. (1987), Fagerholt (1999) and Sigurd et al. (2005), discussed the fleet size and mix models applied to liner service. Lane et al. (1987) provide a dynamic cost-based model that determines the cost-efficient fleet that meets the known shipping service demand. Fagerholt (1999) proposes three methodologies to solve the problem: the generation of feasible single routes, the combination of multiple routes, and the assignment of the routes for the optimal fleet. Sigurd et al. (2005) developed a mathematical model and adopted a Dantzig-Wolfe decomposition model to construct the fleet of ships, a visit schedule, and routes.

It can be noted that no one of those papers discussed the development of a model to search for the optimal fleet for river-sea transport. Even the earlier work of Schwartz (1968) does not consider the river–sea system using river-sea vessels. In this regard, planning the fleet for a liner service adopting river-sea transport is a gap in the literature. Therefore, the main goal of the present work is to develop a mixed integer linear programming model to support the strategic planning of fleet size and mix problems to be adopted in a river-sea liner shipping service.

From the authors' knowledge, the lack of past studies on river-sea liner shipping services in the literature may be because the oldest and most frequent form of river-sea transport relates to the usage of sea-going ships on the sea leg and barges on the river leg, including cargo transhipment from sea-going to barges and vice versa at the junction port. This way, the problem was treated separately, as inland waterways or maritime transport. But, nowadays, river-sea transport also relates to adopting river-sea vessels, which can navigate the sea and river legs without transhipment. The transhipment activities are costly and time expensive, and this cost are not applicable for river-sea vessels. Thus, the present work can advance the state of the art when treating the problem of river-sea transport.

When modelling the maritime transport system, common assumptions include defining the route's origin and destination, voyage duration, sailing speed, demand uncertainty, vessel capacity, and time windows. In maritime transport, the term "time window" mainly refers to the "voyage weather window" or "port time window". The sea-leg operational weather window refers to the weather conditions that allow for safe shipping, including wind speed, wave height, extreme temperatures, and more. In the river leg, the operational weather window mainly concerns tidal and flood conditions, channel maintenance, and other factors. Additionally, the serviceability of each port of call at the expected arrival date is considered the "port time window". Time window conditions may restrict the proper delivery of cargo at the destination port. However, as the paper lies at the strategic level of a river-sea liner shipping service, the proposed fleet size and vehicle routing model assumes that the liner shipping has fixed sequences of ports of call and schedule. This implies that vessels are organised following dispatch orders to reach the maximum traffic capacity of the waterway.

3. Materials and methods

3.1. River-sea transport

As described in section 1.1, the new bauxite supply chain, from Guinea-Africa to Binzhou-China, falls into the river-sea transport, which directly depends on the navigable waterways that provide navigable connections between river and sea basins. This shipping mode is organised by Radmilović et al. (2011) in several forms, such as river-sea with transhipment, technology with river-sea vessels, and river-sea push barge system as a developing system. Those authors presented the main components of a river-sea with a transhipment as a junction port, a river or barges ships, sea ships and port cargo handling with a tug fleet. Furthermore, for the technology with river-sea, the authors highlight the river-sea vessels as the most important component of the system because this vessel type allows shipping through short-sea and overseas routes. Thus, the river-sea push barge system is mainly characterised by short-medium transport distance made by river-sea push barges.

Therefore, considering the new bauxite supply chain, it is possible to characterise the described bauxite shipping as "river-sea with transhipment", which also adopted the "push barges system" and "river-sea ship technology"; the Yantai port represents the transhipment port; barges make the river leg trough Noniz River (Guinea); the overseas route from Africa to China is made by a Very Large Ore Carrier (VLOC); and, the river-sea leg from Yantai port to Binzhou port is made by river-sea vessels. The planning of a heterogeneous fleet of river-sea vessels is the main goal of the present study.

3.2. Strategic planning of fleet size and mix

Many maritime transportation planning problems are encountered at strategic, tactical, and operational levels. According to Brouer et al. (2018), a rough classification of the strategic planning problem can be the markets to serve, the fleet size and mix, and the network design. The service selection, scheduling, fleet deployment, cargo routing and speed optimisation are part of the tactical planning. Thus, empty repositioning, stowage, berth, and disruption management are categorised as operational planning problems.

All these problems present different decisions that impact the operation of the supply chain, and most data are associated with some degree of uncertainty. The study of the risk aspects involved in maritime and port logistics is described in many works, as well as Xu et al. (2023) and Wang and Wang (2023). Sun et al. (2023), specially studied the risk of the bauxite supply chain from Africa to China.

The demand fluctuation over the year directly impacts the shipping revenue (Park et al., 2023). Consequently, establishing an adequate fleet in liner shipping is a medium-long-term plan (6 months to a year) that attempts to maintain regular service with a full payload vessel.

Therefore, the maritime fleet size and mix problem (FSMP) consist of deciding the optimal number of each type of vessel required to deliver the specified demand distribution in each planning period. The integration of the FSMP with the vehicle routing problem (VRP) increases the complexity of the problem but also improves the decision process, guaranteeing the chosen vessels have the precise tonnage capacity to transport the cargo when performing the route (Pantuso et al., 2014). The VRP constraints ensure a proper ship operation.

3.2.1. Model assumptions

In this regard, the present work aims at developing a mixed integer linear programming model (MILP) to solve the fleet size and mix vehicle routing problem (FSMVRP). The Arc Flow formulation is established on a weighted graph, G = (V, A), representing the transportation network. The nodes is a set of vertexes, where V = {0,..,i} includes the customers and depot (located at vertex zero i0), and the set of arcs is represented as A = {(i,j)|i, j ϵ V, i ≠ j}. Generally, the main decisions of the fleet planning problem consist of how many vehicles to acquire, which vessel type to acquire and when to acquire the vessels. In the present model, consideration is given to the design of a brand-new fleet to transport a given demand.

The main modelling assumption of the present river-sea liner shipping is that it has a fixed route and schedule, where the vessels are organised following the dispatch orders to reach the maximum traffic capacity of the waterway. This implies that the problem with the schedule design of the liner service is out of the scope of the paper. Therefore, the impact of the "voyage weather window" or "port time window", the optimisation of the "sailing speed", and other tactical-level planning factors are not considered in this model.

Schematically, the conceptual model can be stated as:

- *Given* the pool of vessels models *m*; the number of vessels *v* per model *m* with the respective vessel model capacity; the period of time *t* (in days); the demand per day *t*; the Yantai and Binzhou locations.
- *Obtain* the time between vertex *i* and vertex *j*, the maximum number of possible voyages from depot i_1 to customer *j* per day *t* per vessel *v* of model type *m*.
- *Subject to* the vehicle routing constraints, the cargo demand restrictions, and the fleet size constraints.

3.3. Mathematical model

The objective of the model is the minimisation of the fixed cost associated with the acquisition of the vessels and, simultaneously, the minimisation of the variable cost associated with the cargo transportation:

$$\sum_t \sum_m RC_m \times fleet_{tm} + \sum_t \sum_m \sum_v \sum_i \sum_j \left(VC_m \times \left(\frac{dist_{ij}}{speed_m} \right) + ExtT \right) \times x_{tijmv} \tag{1}$$

Vehicle routing constraints guarantee that one vessel *v* of model *m*, serve Binzhou *j* once in time period *t* (2) and ensure that when a vessel *v*, model *m*, enters a customer location *i*, it must depart from it (3):

$$\sum_m \sum_v \sum_i x_{tijmv} \geq 1, \forall (t, j | j > 1) \tag{2}$$

$$\sum_i x_{tijmv} - \sum_l x_{tjlmv} = 0, \forall (t, j, v, m) \tag{3}$$

The sub-tour elimination constraints avoid the routes which do not start and end at the Yantai port:

$$u_{ti} - u_{tj} + (MAXVERTEX \times x_{tijmv}) \leq MAXVERTEX - 1, \forall (t, m, v, i, j | 2 \leq i \neq j \leq MAXVERTEX) \tag{4}$$

The demand flow constraints guarantee that the flow of bauxite between vertexes *(i,j)* is higher to or equal to the demand at Binzhou, and the vessels carry the difference between the quantity of bauxite before and after a visit to Binzhou (5). Thus, no flow of cargo demand will be accepted between Yantai-Binzhou *(i,j)* if no route is performed by vessel *v*, model *m* (6). Moreover, the flow of cargo in a voyage departing from the Yantai port (i_1) is constrained not to exceed the capacity of the vessel *v* assigned to perform the voyage (7):

$$\sum_i y_{tij} - \sum_l y_{tjl} = DEMAND_{tj}, \forall (t, j | j > 1) \tag{5}$$

$$y_{tij} = M \times \sum_m \sum_v x_{ijmv}, \forall (t, i, j | i \neq j) \tag{6}$$

$$y_{tij} \leq \sum_m \sum_v CAPACITY_{mv} \times x_{tijmv}, \forall (t, i, j | i = 0, j > 1) \tag{7}$$

The fleet size constraints serve to account for the total number of travel routes assigned to vessel *v* of model *m* in time *t* (8), the number of vessels *v* of model *m* per day *t* needed to accomplish the routes (9), the quantity of type *m* model of vessels *v* is used to attend Binzhou per period of time *t* (10) and the final fleet of vessels of model *m* (11):

$$t_{tmv} = \sum_{j \neq 1} x_{tijmv}, \forall (t, i, m, v | i = 1) \tag{8}$$

$$n_{tmv} \times MAXN_{tmv} \geq t_{tmv}, \forall (t, m, v) \tag{9}$$

$$fleet_{tm} = \sum_v n_{tmv}, \forall (t, m) \tag{10}$$

$$final_m = \sum_t fleet_{tm}, \forall (m) \tag{11}$$

It is important to note that the n_{tmv} term is directly proportional to the number of possible voyages from Yantai i_1 to Binzhou *j* per day *t* per vessel *v* of model type *m*. The MAXN_{tmv} term is the time spent on each route performed by the vehicles.

4. Theory and calculations

The present section aims to verify the solution provided by the model to confirm that the model has built the shipping system correctly while satisfying the specific constraints.

4.1. Model verification

Adopting the Chinese river-sea transport service from Yantai Port to Binzhou Port as the case study, this section describes the system's main features. The Binzhou port is the only customer in the network and the total sea distance from Yantai port to Binzhou port is 192 nautical miles (Table 1). Therefore, the vessels in the analysis present different characteristics, as shown in Table 2. The fixed cost of both vessels is similar because they are the same type of vessel (small bulk carrier). Thus, the main differences in vessels' characteristics are the maintenance cost, fuel cost, cargo capacity and speed. To analyse the model following the demand fluctuation, two small homogeneous scenarios are evaluated, considering the same demand distribution but varying the time window.

Table 1
River-sea distance between the Yantai port to Binzhou port.

Origin	Destination	Sea Distance (NM)
Yantai Port	Entrance of Toaer River	170
Entrance of Toaer River	Bhinzou Port	22

Table 2
Vessel's characteristics.

Vessel type		
Characteristics	Small Bulk Carrier I	Small Bulk Carrier II
Cargo Capacity (DWT)	9,000.00	7,000.00
Average Speed (KN)	9.00	11.00
Fixed Cost (USD/month)	63.83	63.83
Maintenance Cost (USD/month)	7.09	5.39
Fuel Cost (USD/voyage)	7.09	5.39

For the first verification step, the input data for the average demand of 52,000 tons is equally divided into 4,333.33 tons to be delivered in 12 days. The model returns the optimal solution routes performed by the vessels as round trip starting and finishing at the Yantai port. The routes also account for the extra time to load and unload the vessels at the ports. The model defined the Small Bulk Carrier II as the optimal vessel's model to accomplish the daily shipping task. Even with the same daily rate costs between the Small Carrier I and II, the model chose to navigate the routes of the vessels with the smallest capacity, which presents the smallest variable and fuel costs. The objective function equals 7,980.21 USD, with a fixed cost of 25.44 USD and a variable cost of 7,954.80 USD.

A second verification step is proposed, aiming to analyse the impact of demand fluctuation on fleet composition. The average demand of 52,000 tons is equally divided into 8,666.66 tons to be delivered in 6 days. Now, the time window has changed, but the amount of cargo to be delivered remains the same. The established routes for all days do not change when compared with the verification step one, but the most appropriate vessel to accomplish the respective task is now the Small Bulk Carrier I, with a capacity of 9,000 DWT. One ship per day guarantees the delivery of the demand cargo. The objective function equals 5,617.48 USD, with the fixed cost equal to 12.72 USD and the variable cost equal to 5,617.48 USD.

Through this verification process, it is possible to recognise the effect of demand fluctuation on the shipping service imposed by the time window and the model's behaviour to determine the optimal system service. The solutions guarantee that the model solution satisfies the demand flow and vehicle routing constraints.

5. Case study, results and discussion

5.1. Case study

As described in section 4.1, the present model focuses on the river-sea transhipment leg of the bauxite supply chain from Africa to China. The China-Africa trade cooperation started in 2014 (Lei, 2023), and in 2015, 170,000 tons of bauxite from Guinea at Yantai port was the first bauxite transportation (Chuanjiang, 2015). In 2019, a new record in tonnage for bauxite transport was established, 300,000 tonnes of bauxite (35°Nord, 2019). Due to its optimum location as a transhipment port, the Yantai Port has successfully delivered bulk cargo to medium/small-sized ports (Yantai Port Group, 2023). This has been creating a new logistic mode as river-sea transport is performed by sea-going vessels. In the present case study, the river-sea transport starts at China's import/export bauxite hub leader, Yantai Port, and the end customer is the Binzhou Port. The ports of Yantai and Binzhou are part of the coastal port cluster formed in Shandong province (Chuanjiao, 2023). The route has a long sea section and a short river section. There are no government navigation closures for the 14 km in Taoer River. Thus, to avoid the low-water periods and the impact of water flow rates, the vessels must enter the harbour by tide twice daily.

As the fundamental nature of the problem is not homogenous, two fluctuations are established to be analysed: low and high demand. Therefore, the cargo demand during the low season varies from 130,000 to 250,000 tons, and during the high season, it varies between 300,000 and 350,000 tons. Attempting to recognise the effect of the demand fluctuation at the extreme demand points, four scenarios are described, assuming the minimum and maximum demand for the low and high seasons (Table 3). The river-sea distance and the vessel's characteristics remain the same as the ones described above. The Vessel's Characteristics are mainly related to the vessel's cost, which varies not only based on fixed routes but also from country to country. Moreover, the source of data is also scarce because the costs are also established according to the "type of vessel", and, for the river-sea transport, if the river-sea transport is performed by the river-going vessels, it is usually reported as Inland Waterways data, and, if performed by sea-going vessels, reported as maritime data. So, the vessel's characteristics in Table 2 are based on the authors' industry expertise.

The problem appears to be the strategic decision to establish the number of river-sea vessels needed to accomplish the low and high seasons of the bauxite during the year.

5.2. Mathematical model results and discussions

The case instances and the mathematical model are implemented and solved by the IBM ILOG CPLEX Studio Optimisation. To run the Fleet Size and Mix Vehicle Routing MILP model, a workstation with Intel (R) Core(TM) i7 of 2.30 GHz and 16 GB RAM is used. Thus, for each demand scenario, a new solution is encountered.

For all the scenarios, the model maintains the same solution, directly shipping from Yantai port to Binzhou port, designing a round trip voyage of approximately two days (42.9 h), which accounts for the 4h of extra time to load and unload the cargo at the ports (Fig. 2). The realistic data instances do not allow one vessel to accomplish cargo transportation for 30 days, so the model defines the number of ships necessary to realise the shipping service and the respective costs (Table 4).

The fleet composition solution for the minimum demand of the low season appears as the most balanced composition, determining almost the same number of vessels: 7 small Bulk Carrier I and 10 Small Bulk Carrier II. This solution also presents the lowest cost because it is the smallest cargo shipment service regardless of the low or high season. On the contrary, the solution of the maximum demand of the high season determined that the Small Bulk Carrier II is the most optimal vessel to accomplish the estimated cargo, and all the ships travel with a full payload. Thus, because of the high number of vessels in the fleet (39), the fixed and variable costs are the most expensive shipping service.

It is possible to note that the solutions of the low season's maximum demand and the high season's minimum demand are very similar in cost and fleet composition because the cargo demand does not change so much. Both solutions establish a high number of Small Bulk Carrier II and a low number of Small Bulk Carrier I to accomplish the transhipment service.

Thus, the present model appears as a rapid screening tool to be used during the strategic planning of the fleet planning. In addition to

Table 3
Seasonal fluctuation of the customer demand.

Cargo Demand			
Month	Minimum demand (tons)	Maximum demand (tons)	Seasonal time
January February March	130,000.00	250,000.00	Low Season
April May Jun July August September October	300,000.00	370,000.00	High Season
November December	130,000.00	250,000.00	Low Season

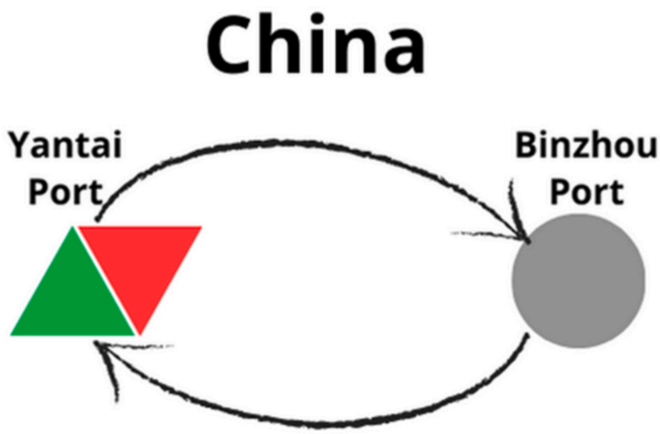

Fig. 2. Travelled routes for all days in the homogeneous and heterogeneous demand.

presenting the fleet composition and shipping cost to different scenarios, the methodology may help the decision makers to identify essential issues of the modelled system, for example, the fleet composition adopting the vessels of Small Bulk Carrier II, capacity of 9,000 DWT, can better accomplish the river-sea transport services, with almost full vessel payload capacity, for all the demand fluctuations and especially when the cargo demand starts to increase until it reaches peak of the demand during the high season. It can reduce the number of vessels transporting cargo from Yantai Port to Binzhou Port and simultaneously reduce fixed and variable costs.

5.2.1. Discussion

The proposed study is primarily a feasibility study of the real-world needs of the industry, to analyse and evaluate potential alternatives for expanding the already-defined bauxite supply chain. Currently, the total tonnage of bauxite liner shipping is nearly 260,000 DWT. To enhance the service level of the shipping service, the strategic planning of a fleet of river-sea vessels in a liner shipping service appears to be a significant topic.

Adopting river-sea vessels presents superior navigation characteristics, enabling the overpass of adverse weather conditions at the sea leg, which is a crucial aspect for this defined bauxite chain, given the route comprises a lengthy sea section and a brief river section (see Table 1). Consequently, the quantified decision support model presented in this paper assists decision-makers in establishing an appropriate fleet for liner shipping, ensuring that the selected vessels have the requisite tonnage capacity to transport the cargo along the designated route.

Furthermore, as evidenced by the results, the model indicates that river-sea transport without transhipment, involving a direct shipping route from Yantai port to Binzhou port, represents the optimal route. The rapid screening tool also suggests that both vessels are competitive when demand is at its lowest during the low season. However, when demand reaches its maximum during the high season, the ship with the higher capacity is the most feasible to accomplish the routes.

6. Conclusions

The mathematical approach provided in this work develops a fleet size and mix vehicle routing model aiming at helping decision makers during the strategic fleet size planning of a river-sea liner shipping. The developed methodology serves as a rapid screening tool capable of determining the fleet composition and shipping costs for different scenarios and highlighting important issues of the modelled system. The strategic model allows the decision-makers to analyse the impact of the demand fluctuation over the year by running different demand scenarios without spending considerable computational effort and time.

A model verification is presented, attempting to test the behaviour of the solutions offered by the model and analysing if the established solutions satisfy the specific constraints. For this purpose, two small homogeneously data instances are tested. Furthermore, a case study is performed and discussed to analyse the impact of a realistic demand fluctuation.

As the paper's main contributions, it is possible to identify that river-sea transport without transhipment is a sustainable, reliable, and cost-effective mode of transportation, which may improve the shipping service level and local economy. On the one hand, the demand allocation, fleet size, and composition are part of the logistic infrastructure design, which directly impacts the efficiency and effectiveness of bauxite shipping. Therefore, the model contributes to the maximisation of resources and, simultaneously, the minimisation of logistics costs. On the other hand, the example of the river-sea transport without transhipment in Shandong province is a perfect example of how the economy can grow with the creation of port clusters when major ports, such as Yantai port, integrated with medium/small ports, such as Binzhou port. Therefore, the strategic fleet size and mix vehicle routing model for river-sea liner shipping is a valuable discrete tool that helps decision-makers define and adjust fleet size and composition in uncertain demand scenarios.

The developed quantified decision support model improved the service level of the shipping service by establishing an adequate fleet in liner shipping, guaranteeing that the chosen vessels have the precise tonnage capacity to transport the cargo when performing the route. This reduces the frequent mismatches between fleet capacity and demand. The proposed liner shipping assumes a fixed sequence of ports of call and schedule, which guarantees that vessels are organised following dispatch orders to reach the maximum traffic capacity of the waterway. As future work, the study can benefit from an uncertainty optimisation approach, as adopting a stochastic programming model allows the decisions to depend on the probabilistic knowledge of the uncertain demand. Moreover, the voyage schedule design problem of a liner service is out of the scope of the paper; therefore, the impact of the "voyage weather window" or "port time window", the optimisation of the sailing speed, and other tactical-level planning factors are not considered in this model.

CRediT authorship contribution statement

L.M.R. Silva: Writing – original draft, Visualization, Investigation, Formal analysis. **Haiyan Wang:** Writing – review & editing, Conceptualization. **C. Guedes Soares:** Writing – review & editing, Supervision, Conceptualization.

Table 4
Fleet compositions and shipping costs for the heterogeneous demand scenarios.

Demand Fluctuation		Fleet Composition	Shipping Cost			Solution Time (s)
		[m1, m2]	Fixed Cost (USD)	Variable Cost (USD)	Total Cost (USD)	
Low Season	Min. demand	[7,10]	36.04	13,982.00	14,017.59	0.31
	Max. demand	[7,23]	63.60	26,125.00	26,188.80	0.54
High Season	Min. demand	[3, 31]	72.08	30,947.00	31,018.69	0.81
	Max. demand	[0,39]	82.68	36,431.10	36,513.62	0.94

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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