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Exploring the effectiveness of West African ports as a hub in the transatlantic logistics: a multi-criteria approach

Paulo Correia
Shanghai Maritime University, Institute of Logistics Science and Engineering, 1550 Haigang Avenue, Pudong New Area, Shanghai 201306, China, correiapaulo90@gmail.com (corresponding author)
Chengji Liang
Shanghai Maritime University, Institute of Logistics Science and Engineering, 1550 Haigang Avenue, Pudong New Area, Shanghai 201306, China, liangcj@shmtu.edu.cn

Keywords: Pareto optimal, asymmetric hub system, nonlinear optimization, West Africa, shipping emissions and multi-gateway port model.
Abstract: Logistics costs account for up to 75% of the price of African goods, making them a greater trade barrier in Africa than tariffs and trade restrictions. Improving delivery efficiency is therefore critical for enhancing trade competitiveness. This paper examines the effectiveness of West African ports as a hub, proposing an asymmetric hub system that links West Africa, Europe, and South Americas transatlantic supply chain, and compares it with a traditional multi-gateway configuration. A multi-objective optimization approach based on the e-constraint method is adopted to generate the Pareto frontier between conflicting liner shipping goals- cost reduction, environmental sustainability, and on-time service performance. The results highlight a strong empirical correlation between emissions reduction, fuel efficiency, and liners tactical decisions, contrasting on-time/ cost performance. This finding predicts liner's support for a higher probability of failure for on-time delivery under energy efficiency scenarios, whereas the opposite is also true, that is, improving customer service for high pollution. However, given the above goal conflicts, the analysis reveals a clear macro-level tradeoff between hubbing and de-hubbing strategies. Overall, the results suggest that adopting an asymmetric hub system can enhance West Africa trade competitiveness and sustainability. These insights should encourage policymakers to prioritize strategic hub-port investments and provide liner operators with a set of Pareto-optimal solutions for redesigning logistical networks that better balance cost, service, and environmental performance across the transatlantic supply chain.

1 Introduction

Containerized liner shipping, as a fundamental actor in the global supply chain, is expected to operate with high efficiency, i.e., low costs, on-time delivery, and net zero carbon dioxide emissions. Logistics service costs, in particular, have been continuously increasing over the last years; of these costs, transportation accounts for the largest share (60-80%), followed by carrying costs (15-30%), and administrative costs (5-10%) varying across countries [1]. Although an increase in logistics costs can be tied to market growth, studies have shown that logistics costs in emerging economies are significantly higher- often accounting for 10-20% of a country's GDP- compared to less than 10% in more developed, efficient economies. For example, logistics costs within/to the African region are among the highest globally [2], affecting African costs of finished goods and trade competitiveness. Stated somewhat more specifically, the high transport costs account for up to 75% of the price of African goods [3] and represent a more significant barrier to trade in sub-Sharan Africa than terrifies and trade restrictions, leading to an estimated export loss of $65 billion annually [4].

Supply chain management literature and practice underscore several strategies that can be adopted to mitigate logistics costs. One commonly adopted strategy entails combining multiple shipping routes, such as those connecting West Africa, Europe, and South America via centralized or decentralized transshipment nodes that benefit from economies of scope. This, then, increases traffic density, leading to economies of density and a reduction in the logistics costs known as economies of scale [5]. Aware, the West African governments aim to transform their port into logistic services centers for international trade and regional gateway/hub ports through large investment campaigns [6].

Establishing a hub port within the West African region (Figure 1) is critically relevant to the economic integration of its countries into the global trade system. Given its strategic location at the Atlantic crossroads between Africa, Europe, and the Americas, such a hub could significantly reduce logistics costs. However, whether this economic gain (e.g., economies of scale) is sufficiently great depends on various spatiotemporal factors, including supplier-customer geographical distances (West Africa, Europe, South America), cargo volumes, daily operational costs, and the efficiency of other distribution systems (e.g., multi-gateway port model). At the same time, cargo consolidation increases fuel costs and emissions by raising resistance to displacement- a critical factor often overlooked in previous literature proposing hub distribution systems- contrasting for example the multi-gateway port model balanced cargo distribution. For sub-

Saharan Africa (SSA), which is among the most vulnerable regions to climate change, the environmental impact of vessel displacement cannot be overemphasized. This, then, justifies the need to investigate the proposed asymmetric hub system effectiveness versus the traditional multi-gateway port model in West Africa before any policy reforms or significant investment campaigns.

In a hub location problem, liner shipping must decide on the optimal hub port location and logistical network design (e.g., routing planning, fleet deployment, and schedule design) centered around the identified hub. Many tactical or operational decisions that liners have to make throughout the logistics network design are conflicting in their nature. It follows that providing on-time logistics services (reliable) entails major capital outlays for deploying a designated number and type of vessels. Still, in modern times, characterized by short life cycles products, and consumerism, adopting higher speeds has become necessary. Although both techniques can improve shipping schedule , they also lead to elevated vessel fuel consumption, environmental impacts, port-related fees (pilotage, towage, mooring), and other vessel-related handling expenditures. Contrariwise, high shipping time (service unreliability) leads to a substantial rise in logistics costs/time such as inventory holding costs, charter costs, and hidden customer dissatisfaction costs. Withal, prior research on hub location problems usually model's liners objectives as a consolidated goal, overlooking important tradeoffs, and/or proposed costs versus pure time-minimizations, which is still limiting in the above context. To explore this gap in the literature, this paper addresses these issues from a multi-criteria approach. In other words, this study proposes a nonlinear mixed-integer multi-objective optimization framework that disentangles the main cost components of liner shipping- previously aggregated in the literature-into distinct and competing categories, using a similar approach comparable to that of reference [7]: costs that usually decrease with time, and costs that commonly increase with time. The primary purpose is to investigate the effectiveness of the proposed asymmetric inter-hubs and spoke system compared to the current multi-gateway port model from three perspectives: logistics costs (logistical economic perspective), delivery unreliability (economic and customer-service perspective), and environmental sustainability (societal-environmental perspective). The cost-tradeoff is assessed using the e-constraint method.

Following this introduction, this paper unfolds as follows: The next section is dedicated to the relevant literature. The third section defines the problem of this study. The fourth section designs the mathematical model. The fifth section depicts the data utilized in this study, and the sixth is the solution approach and analysis. Moreover, the final section is the summary of the study.

2 Literature review

The problem of moving goods across the supply chain from supplier to customer has received significant attention from the research community. One commonly employed strategy involves moving goods via transshipment hub facilities, leading to hub location problems. Literature regarding the hub location problem has been thoroughly reviewed by [5]. The authors emphasized the relevance of economies of scale to this type of problem, which early literature poorly captured. Furthermore, the importance of economies of density and spatial scope cannot be overemphasized. [8] provided a detailed survey of existing studies on liner shipping routing and scheduling, with particular emphasis on the development of optimization models, solution algorithms, and underlying assumptions in this field. The literature review also encompasses various planning levels, including strategic aspects such as determining fleet size and designing the broader logistical network, tactical decisions such as setting service frequencies and allocating vessels, and operational concerns involving container assignment, route adjustments, and rescheduling procedures. The study concludes by identifying key directions for future research, especially in enhancing delivery reliability and promoting logistics sustainable practices.

As discussed earlier, decisions in liner shipping at these three levels often conflict. However, most traditional models in the literature usually combine conflicting objectives into a single one, limiting crucial tradeoffs. Only a few studies address these conflicting objectives, primarily focusing on tactical decision levels in liner shipping.

For example, [7] examined the vessel scheduling (tactical level) problem and introduced a global multi-objective optimization algorithm using the epsilon-constraints method to handle the conflicting objectives. Numerical experiments conducted on the Asia-Mediterranean Sea route revealed through sensitive analysis that vessel schedules are more responsive to fluctuations in fuel costs than to changes in emissions costs.

[9] investigated the conflicts between fleet deployment costs (tactical decision levels), transportation time, and emissions, proposing a weighting method to analyze crucial tradeoffs between pure cost and time minimization and between cost and emissions. Numerical experiments suggested that cost reduction could be achieved through longer transportation times.

[10] examined green vessel scheduling (tactical decision levels) and proposed a multi-objective model to reduce costs, emissions, and service unreliability. Computational experiments showed that port congestion's impact on delivery unreliability is more significant than its effects on additional costs and emissions.

[11] addressed the vessel scheduling (tactical decision levels) recovery problem by proposing a multi-objective model to reduce late arrival costs and total profit loss during disruptive port events. Numerical experiments along the Europe-Pakistan route demonstrated that the model can efficiently generate a set of Pareto-optimal solutions. Yet, a significant body of literature has taken an

alternative approach, merging conflicting objectives into a single objective function; see for instance, [12-16].

2.1 Contribution

1) Few studies have explored the role or effectiveness of West African ports as a hub center within the transatlantic logistics network, which connects West Africa, Europe, and South America. Moreover, existing research often combines conflicting objectives into a single objective function, overlooking important tradeoffs. This study aims to address these gaps in the literature and proposes an asymmetric hub delivery system.
2) Existing studies provided limited if any, insights into comparing the asymmetric hub system in maritime logistics with the multi-gateway port system. This study fills this gap in the literature by offering a detailed comparison from a multi-criteria optimization approach.
3) This paper focuses on the West Africa, Europe, and South American transatlantic supply chain, a corridor characterized by historical trade relationships, recent increases in cargo throughput, and strategic positioning at the Atlantic shipping crossroads. Research on these regions provides valuable insights into the relevance of hub distribution systems when compared to other systems such as multi-gateway.

3 Problem description

This section outlines the problem description, focusing on key decisions related to hub location and main liner shipping features, including (i) network design decision, (ii) vessel deployment, (iii) vessel operational cost, (iv) vessel fuel consumption, (v) vessel emission, and (vi) port time windows.

3.1 Routes, fleet deployment, and hub location problems

Container cargo is typically transported by vessels deployed in a set of optimal routes. Let P = $\{1\ldots, n_p\}$ represent the set of available port calls and let k ∈ K (K= $\{1,2, \ldots, n_k\}$) denote the set of available vessels that can be assigned to a ship route r ∈ R. for a given ship type k a binary variable x_{ijk} is introduced, taking a value of 1 if the vessel is assigned to travel between port pair (i, j) ∈ P, and 0 otherwise. Furthermore, the segment connecting two subsequent ports (e.g., port i to j) is defined as a voyage leg (e.g., voyage leg i ∈ I). Let h ∈ H_p(H_p= $\{1, 2\ldots n_{H_p}\}$) be a subset of P representing potential hub ports. A binary decision variable $\bar{y}_{H_p}$ is introduced, taking the value of 1 if port h ∈ H_p is designated as a hub, and 0 otherwise. The optimal hub location is determined using a p-hub center approach.

Six potential hub ports were selected based on previously discussed port investment initiatives and the growing cargo volumes [6]. These are the port of Abidjan, port of Dakar, port of Tema, port of Lomé, port of Lagos, and port of Praia, (Figure 1). In addition, key existing hub ports- Tanger Med, Las Palmas, and Antwerp- were considered to assess their influence on hub port selection in West Africa, as they currently serve as primary hubs along the West Africa-Europe-South America transatlantic logistics network.

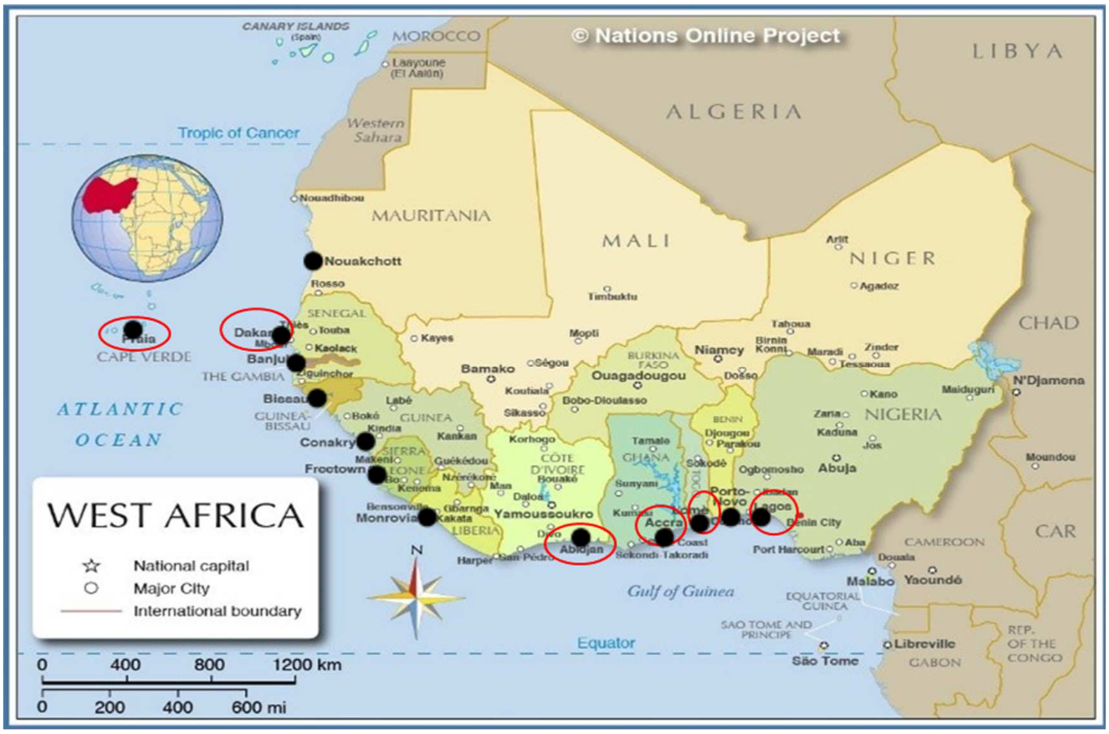

Figure 1 Map of West African nations, showing active ports (dots) and candidate hub ports (circles) [17]

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The port of Algeciras was chosen as the representative hub for Europe, while the port of Santos was selected for South America. The designed destination ports function as regional hubs, forming an asymmetric hub and spoke network. In such a structure, a central hub e.g., West Africa- serves as the main connection point, linking to all other hubs (e.g., Europe and South America). However, direct connections between non-central hubs, e.g., Europe and South America, are absent, (Figure 2).

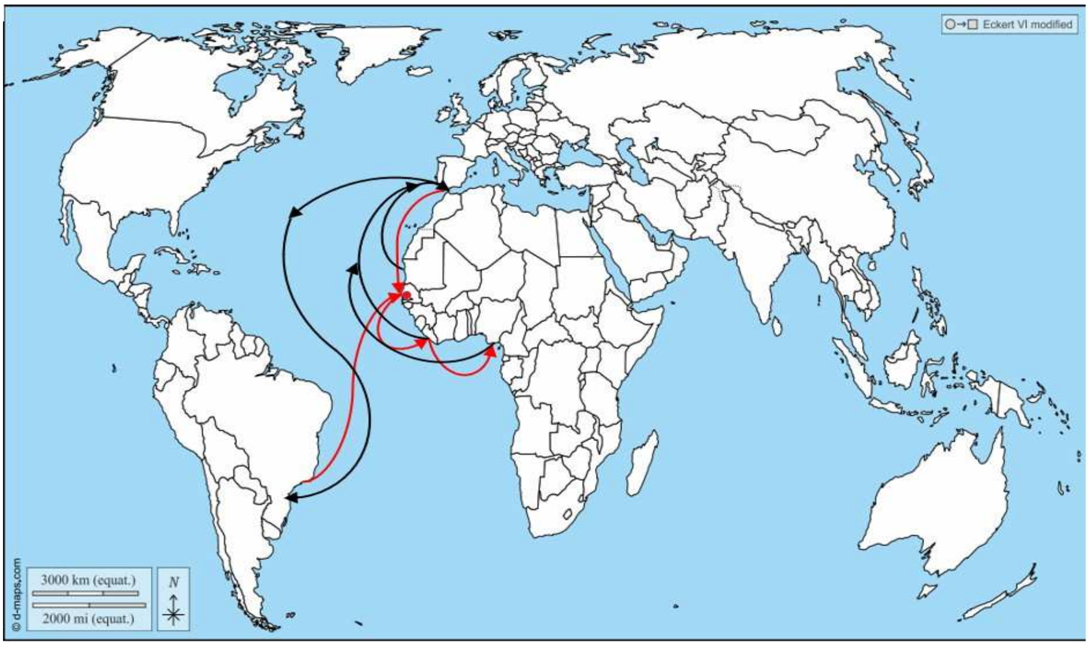

Figure 2 Map showing transatlantic routes for West Africa-Europe-South America trade under two different models: the asymmetric hub port approach (red lines) and the multi-gateway strategy (black lines)

3.2 Vessel operational cost

The main operational expenses for a vessel include port fees, container handling costs, and sailing-related expenses. Sailing-related costs encompass both fuel and operational expenditures. Fuel costs are directly linked to the vessel fuel consumption and prevailing prices [18]. The fuel cost for a vessel operating on voyage leg i ∈ I_r within route r ∈ R can be determined using the following equation (1):

$$VFC_{rik} = f^p . \sum_{r \in R} \sum_{i \in I_r} \sum_{k \in K} vfc_{irk} \quad (1)$$

Where:
f^p - represents the fuel price (USD)
vfc_{irk} $r \in R$, $i \in I_r$, $k \in K$ - denotes the vessel fuel consumption on voyage leg *i* of route *r* considering a specific vessel type *k*.

The daily charter and vessel operating costs are influenced by several factors, such as vessel size, crew, insurance, repair and maintenance, stores and lubes, and administration [18,19]. The daily charter and vessel operating cost in the ship route $r \in R$ can be estimated as follows (2):

$$VOC_r = \alpha_1 . Cap_k{}^{\alpha 2} \quad (2)$$

Where:
α_1 - is the charter cost parameter (USD), Cap_k - is the capacity (ton) of vessel k. $\alpha 2$ is the factor modeling the effect of economies of scale due to the vessel size, $0 < \alpha 2 \leq 1$.

The port-related expenses primarily consist of cargo handling charges and port dues. Port dues represent the fees incurred at each port for towage, mooring, and pilotage. At port p ∈ P within a given ship route r ∈ R, The port dues were estimated using a linear regression model based on actual cost data obtained from West African port authorities. The estimation formula is (3):

$$PDC_{pr} = SL_{p \in P} . Cap_k + in_{p \in P} \quad (3)$$

Where:
$SL_{p \in P}$ - represents the regression slope for port $p \in P$;
Cap_k– is the capacity of vessel $k \in K$;
$in_{p \in P}$ - is the intercept of the regression model for port $p \in P$.

The cargo handling Fees (THC) cover loading and unloading operations at each port along a vessel route. The total cargo handling charge at port $p \in P$ in shipping route $r \in R$ is estimated as (4):

$$THC_{pr} = q_i c_{i \in P}^{hand} + \frac{1}{2} \sum_{h \in H_p} c_{h \in H_p}^{hand} (2q_i) \quad (4)$$

Where:
$c^{hand}_{p\in P}, c^{hand}_{h\in H_p}$- are the unit handling cost (USD) parameters at port *i*, $i \in P$, and hub port *h*, $h \in H_p$. q_i- represents the number of containers (TEU/week) transferred at the hub port $h \in H_p$. In addition, the container-related costs along the ship route $r \in R$ are computed based on the container's usage (lease expense) and the inventory holding cost. These costs are influenced by: (1) The unit daily rental cost for each container (USD/day); (2) The unit hourly inventory cost for each container (USD/hour); and (3) the total transit time (in sea and ports) along the West Africa-Europe-South America transatlantic logistics network.

3.3 Ship sailing speed

Reducing vessel speeds (slow steaming) is a common strategy to decrease fuel consumption and lower carbon emissions. However, it also impacts the ship's transit time. The sailing time for a given shipping leg $i \in I_r$ within route $r \in R$ is estimated as follows (5):

$$SST_{ri} = \frac{Dis_{ir}}{V_{irk}} \quad (5)$$

Where:
$Dis_{ir}(i \in I_r, r \in R)$ is the distance of shipping leg $i \in I_r$ within route $r \in R$.
$V_{irk}(i \in I_r, r \in R, k \in K)$ is the sailing speed on the leg $i \in I_r$.

3.4 Ship fuel consumption

A vessels fuel consumption on a given route is influenced by multiple factors, including sailing speed, weather conditions, hull conditions or its payload, deep water, and ship geometry. Many prior studies on fuel consumption optimization focus on speed as the primary determinant of fuel consumption. Typically modeled using a power-low relationship (6), [20].

$$VFC_{irk} = \frac{\hat{y}_k (V_{rik})^{\text{ŋ}_k - 1}}{24} \quad (6)$$

Where:
$\text{ŋ}_k, \hat{y}_k$ $(k \in K)$ are the vessel-specific parameters characterizing fuel consumption behavior.

3.5 Ship emission

The amount of emission a vessel produces is directly correlated with its fuel consumption and emission factor at sea. This study primarily considers carbon dioxide (CO2) emissions in the sea. Other greenhouse gases (GHGs), such as Sulphur dioxide (SO2), might be reduced by lowering fuel Sulphur content or implementing technical measures, such as exhaust gases filters [9]. The emission and emission cost at ship leg $i \in I_r$ of route $r \in R$ can be estimated as follows (7), (8) [20]:

$$VE_{irk} = ef.Dis_{ir}.Vfc_{rik} \quad (7)$$
$$VEC_{irk} = ecp.\sum_{i\in I_r}\sum_{r\in R}\sum_{k\in K} VE_{irk} \quad (8)$$

Where:
ef - represents the emission factor in the sea (tons of emission per tons of fuel).
ecp - (USD per ton) represents the unit cost of emission.

3.6 Port time window

The maritime container terminal operator might define a specific time window start (TW^{start}_{ir}) and time window end (TW^{end}_{ir}) at each port for vessel arrivals and departures. This paper assumes that service at port begins immediately upon arrival. If a ship arrives too early, before time windows start (TW^{start}_{ir}), it must wait in a designated area. If it arrives late, a penalty cost is incurred, estimated as follows (9):

$$LAC_{rik} = \sum_{r\in R}\sum_{i\in I_r} LC_{ri}\,.\,LAT_{rik}, \forall r \in R, i \in I_r \quad (9)$$

Where:
LC_{rik} represents the late arrival cost parameter (USD) in the port of call *i* on the ship route *r*. LAT_{rik} is the late arrival time.

4 Methodology

This paper adopts a quantitative modeling approach using a multi-objective mixed-integer nonlinear programming (MINLP) scheme. The research procedure involves: (1) formulating a mathematical model that captures conflicting goals in liner shipping, including cost efficiency, logistics service performance, and environmental sustainability; (2) collecting real-world operational data; (3) implementing the e-constraint method with CPLEX to generate Pareto-optimal solutions. The following subsections provide further details on the model formulation and solution procedure.

4.1 Mathematical model

This paper proposes a bi-objective mixed integer nonlinear programming (MINLP) formulation that minimizes the main production costs of a liner shipping route. The costs are divided into two conflicting groups: Z1- costs that rise with transit time, (1) daily vessel charter and operational expenses (VOC), (2) container leasing fees at sea and in port (Clease), (3) inventory holding cost in the sea as well as at ports (CINV); (4) late penalties cost (LAC); (5) terminal-handling charges (THC); and Z2- costs that decrease with transit time, (6) ship emission cost in the sea, (7) vessel fuel consumption cost, (8) port dues (PDC).

Nomenclature

Sets
P= $\{1,2, \ldots, n_p\}$ set of port of call
K= $\{1,2, \ldots, n_k\}$ set of available ship's (ship types)
H_p= $\{1, 2... n_{H_p}\}$ set of hub port

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Binary variable

x_{ijk} =1 if ship of type k navigates the shipping leg from port i to j, (=0 otherwise)

$\bar{y}_{H_p}$ =1 if port $h \in H_p$ is selected to be a hub port, (=0 otherwise)

w_{ih}- 1 if port i is served from hub h, (=0 otherwise)

$g_{i,j,k,s}$ binary variable indicating whether the discrete speed s is selected for the route (i, j) by a ship of type k

Auxiliary variables

t_{ik} arrival time (hours) of ship k at pot i

u_{ijk} travel time (hours) on the sip leg from port i to j with ship k

tlh_k late arrival time of a ship of type k at the hub port h

z_{ijk} =1 if ship of type k navigates the shipping leg from port i to j, (=0 otherwise)

Parameters

n_k quantity of available ship's

n_p available number of ports.

n_{H_p} available number of potential hub ports

dis_{ij} distance in the shipping leg from port i to j (nmi)

tc_{hk} transshipment time at the hub port h

$V_{rik}{}^{min}$ minimum ship sailing speed (knots)

SL_i slope for the equation of simple linear regression to approximate the port due cost at port i

in_j intercept for the equation of simple linear regression to approximate the port due cost at port i

Pt_i port time at port i (hours/day)

Q total amount of containers (TEU)

q_j weekly amount of container loaded at port i (TEU)

w^{Q_r} average container weight (20-ft container tons/TEU)

w_{lk} lightweight of ship k (tons)

w_{tk} deadweight of ship k (tons)

ef ship emission factor at sea (tons of emissions per ton of fuel)

ecp unit cost of emission (USD per ton)

fp fuel price (USD)

lc late arrival cost (USD/hour)

c_i^{hand} container handling cost at port i (USD/TEU)

Cap_k total carrying capacity of a ship of type k (tons)

sf_{ij} unit container freight rate for delivery of cargo from port i to j

$\underline{n}_k, f_k$ fuel consumption function coefficients

α_1 charter cost parameter (USD)

$\alpha 2$ factor modeling the effect of economies of scale due the vessel size, $0 < \alpha 2 \leq 1$.

c_r^{lease} unit rent cost for each container (USD/hour)

$$Z_1 = \sum_{i,j \in P} \sum_{k \in K} \left(\frac{\alpha_1 * Cap_k{}^{\alpha 2}}{24}\right) * w_{ijk} + \sum_{i,j \in P} \sum_{k \in K} \left(\frac{c_r^{lease}}{24}\right) * w_{ijk} + \sum_{i,j \in P} \sum_{k \in K} c^{ivt} * w_{ijk} + \sum_{k \in K} (lc * tlh_k) + \sum_{i,j \in P} \sum_{k \in K} SL_j * LOA_k + in_j * x_{ijk} + \sum_{i,j \in P} \sum_{k \in K} q_j * c_j^{hand} * x_{ijk} + \frac{1}{2} c_h^{hand} \sum_{i \in P} (2q_i) \tag{10}$$

$$Z_2 = \sum_{i,j \in P} \sum_{k \in K} SL_j * Cap_k + in_j * x_{ijk} + \sum_{i,j \in P} \sum_{k \in K} (ef * ecp * dis_{ij} * x_{ijk}) * vfc + \sum_{i,j \in P} \sum_{k \in K} (fp * dis_{ij} * x_{ijk}) * vfc \tag{11}$$

s.t.

$$Z_1 \leq e_1 \tag{12}$$

$$Z_2 \leq e_2 \tag{13}$$

$$\sum_{h \in H_p} \bar{y}_{H_p} = P \tag{14}$$

$$\sum_{i \in P} w_{ih} = 1, \sum_{i \in P} w_{ih} - \bar{y}_{H_p} \leq 0, \ \forall i \in P, h \in H \tag{15}$$

$$\sum_{i \in P} x_{ihk} \leq 1, \sum_{i \in P} x_{hik} \leq 1, \ \forall k \in K \tag{16}$$

$$\sum_{k \in K} Y_{hjk} \geq 1, \forall j \in P \tag{17}$$

$$\sum_{i \in P} \sum_{k \in K} x_{ijk} = 1, \ \forall i \in P, i \neq j \tag{18}$$

$$\sum_{j \in P} x_{ijk} - \sum_{j \in P} x_{jik} = 0, i \in P, k \in K, i \neq j \tag{19}$$

$$\sum_{i \in P} q_i . \sum_{j \in P} x_{ijk} \leq Cap_k, \sum_{j \in P} q_j . y_{hjk} \leq Cap_k, k \in K \tag{20}$$

$$\sum_{j \in P} \sum_{k \in K} q_j . y_{hjk} \geq \sum_{j \in P} q_j \tag{21}$$

$$t_{hk} \geq 168, \ \forall k \in K \tag{22}$$

$$tlh_k \geq t_{hk} - 168 - M_1(1 - x_{ihk}) \ \forall k \in K, i \in P \tag{23}$$

$$t_{ik} + Pt_i + dis_{ij} * \frac{1}{V_{rik}} - t_{jk} \leq M_1(1 - x_{ijk}) \ \forall k \in K, i, j \in P, i \neq j, i \neq h \tag{24}$$

$$w_{ijk} + M_2(1 - x_{ijk}) \geq (t_{jk} - t_{ik}) * q_i - M_2(1 - z_{ijk}) \ \forall k \in K, i, j \in P, i \neq j, i \neq h \tag{25}$$

$$w_{ihk} + M_2(1 - x_{ijk}) \geq (t_{hk} * q_i) - M_2(1 - z_{ijk}) \ \forall k \in K, i, j \in P, i \neq j, j \neq h \tag{26}$$

$$x_{ijk} \leq z_{ijk}, \ \forall k \in K, i, j \in P, i \neq j \tag{27}$$

$$x_{ijk} \geq z_{ijk} - 1, \ \forall k \in K, i, j \in P, i \neq j \tag{28}$$

$$x_{ihk}, y_{hjk} \in \{0,1\}, \ \forall k \in K, j \in P, i \in P \tag{29}$$

$$V_{rik}{}^{min} \ Q, q_j \in N \tag{30}$$

$$lc, ef, dis_{ij}, tlh_k, Pt_i, tc_{hk}, ecp, c_j^{hand}, t_{jk}, u_{ijk}, sf_j \in R^+ \tag{31}$$

Objective function (10) seeks to reduce liner shipping costs that usually increase with time: vessel daily charter and operating cost, container lease cost in sea as well as at ports, inventory-holding cost in sea as well as at ports, vessel late penalties cost, and terminal handling costs. The model objective function, shown in (11), aims to minimize liner shipping costs that commonly decrease with time: vessel emission cost in the sea, vessel fuel consumption cost, and port due cost. Constraints (12) and (13) introduce an epsilon-bound formulation, ensuring that one objective remains within a specified limit while optimizing the other. Constraint (14) indicates that exactly P hub should be selected, whereas constraint (15) ensures that each port can be served by exactly one hub. Constraints (16)-(18) indicate the ship's types for each liner shipping route generated. Constraint (19) is the flow conservation constraint. Constraint (20) sets an upper bound on the container transported, ensuring it remains within the ship's capacity. Constraint (21) guarantees that all the containers transported to the hub port will be further transshipped to their final destination. Constraint (22) sets the time window, where 168 denotes the number of hours in one week. Constraint (23) is a late array. Constraints (24)-(28) specify transit time calculations for the vessel, where the parameter q_i (TEU/time) captures the product of the total container volume on board and the sailing time along a specific route. Given that the maximum sailing duration between any origin-destination pair in this study area does not exceed eight weeks, upper bounds for parameters for M_1, M_2 can be estimated as follows: M_1=8 weeks*168 /h week, $M_2=M_1*\sum_{j\in P} q_j$. Constraint sets (29)-(31) define the characteristics of the model parameters and decision variables.

4.2 Data specification

The container cargo volume (TEU) between the origin and destination serves as a key input for the logistical network. However, such data were not available for this study region. To address this, trade values of containerizable commodities were aggregated from WITS (World Integrated Trade Solution) and converted into container volumes using the approach outlined in [21]. For landlocked countries such as Mali, Niger, and Burkina Faso, the trade value was assigned to the nearest strategic port for simplification. Vessel specifications such as lightweight and deadweight were derived from Marine Traffic and Hapag-Lloyd websites, with computations based on [22]. The Port dues, covering towage, mooring, and pilotage (in and out), were estimated using a linear regression model based on actual cost data from West African port authorities. At most West African ports, Gt_k (gross tonnage) is the standard metric used to calculate charges for pilotage, towage, and mooring. The nautical distances (nmi) between ports were obtained from searates, whereas the average time spent at ports was sourced from UNCTAD. The terminal handling charges were retrieved from West African port authorities. Due to missing data, the port time for Bissau was approximated using the Banjul value.

The late arrival cost parameter is set at 5000 US$/hr., the emission cost parameter at 32 US$, and the emission factor at sea is set at 3.114, while parameters such as $f_k = 0.012$, η_k=*3.0*, c^{ivt}=0.25US$/hour/TEU, moreover the ship minimum sailing speed is set at 15 knots following [20]. The fuel price is assumed to be 484 US$ per ton [19]. α1 is adjusted to 100US$/day·ton$^{\alpha 2}$, α2 = 0.6257, and the container lease cost is set at US$4.5/TEU/day following [18]. The average transshipment time per container is approximated using the ratio of average cargo throughput to the average time a container vessel spends at the port. For example, according to the World Bank and the United Nations Conference on Trade and Development, Senegal handled approximately 696,899 TEU in 2020, with an average container vessel port stay of 0.8 days, resulting in an estimated handling productivity of 99 TEU/ hr.

4.3 Solution methodology

The proposed bi-objective model is nonlinear due to the vessel fuel consumption and sailing time components. Various techniques have been proposed to address the nonlinearity of the fuel consumption function concerning vessel speed, including (1) the enumeration method- which assumes a fixed, predetermined vessel sailing speed across all voyage legs of the liner shipping route; (2) dynamic programming method- which reduces the vessel routing and scheduling problem to the shortest path problem on a time-space network, where the horizontal axis represents time (typically in days) and the vertical axis represents the ports of call; (3) discretization method- involves discretizing the vessel sailing speed, and estimating the nonlinear fuel consumptions for each discretized vessel speed value; (4) tailored method-where the nonlinear vessel fuel consumption function is approximated using techniques such as piecewise linear secant approximating function or tangent lines, and other methods as discussed in detail by [7]. The first method is generally considered unrealistic as liner shipping may adjust vessel speed at the voyage leg in a shipping route. Furthermore, the accuracy of discretization and dynamic programming methods depends on the discretization level, and the accuracy of tailored methods depends on the number of segments defined to approximate nonlinear fuel consumption and usually involves a cost tradeoff: Increasing the number of segments or discretization levels improves accuracy at the cost of high computational time. This paper adopts the discretization method to approximate the nonlinear vessel fuel consumption. Specifically, the vessel sailing speed is discretized into a finite set S={1,2,..,n}, and the fuel consumption is calculated for each discretized sailing speed value. Let $g_{[i,j,k,s]}$ represent the binary variable indicating whether the discrete speed s is selected for the route (i,j) by a ship of type k. To ensure that a speed is only selected for active routes, the following relationship is defined: $g_{[i,j,k,s]} = x_{[i,j,k]}$, ensuring that for any active route (i,j), exactly one speed s is selected by a ship of type k. The selected discrete speed is then used to estimate the vessel fuel consumption on each route pair (i,j) served by a ship of type k: $fuelC_{[i,j,k]} = \sum_s g_{[i,j,k,s]}$. VFC_{irk}, where VFC_{irk} represents the fuel consumption rate corresponding to speed s. The sailing time for each route pair (i,j) can be further linearized by using the reciprocal of the selected speed s.

Due to the bi-objective nature of the proposed mathematical model, there is no optimal solution that satisfies both objectives; rather, there is a set of non-dominant solutions that form the Pareto optimal set. Stated somewhat differently, in multi-objective optimization, the Pareto optimal set comprises solutions from the objective functions, where improving one can only be achieved at the expense of worsening the other [6]. Various techniques have been developed to tackle multi-objective problems and construct the Pareto set. This paper applies the epsilon constraint method, chosen for its robustness in handling the non-convex functions often encountered in real-world contexts. Stated somewhat more specifically, one objective is treated as the primary optimization goal, while the other is incorporated as a constraint. In addition, the Pareto optimal set is constructed by varying the epsilon values applied to the constrained objective. This, in turn, requires that the upper bound interval for epsilon be determined as follows: $epsilon = \frac{Z_2(1) - Z_2^*(Z_1)}{npf-1}$; S.t., $Z_2^*(Z_1)$ is the optimal value of Z_2 when (Z_1) is regarded as a constraint, and $Z_2(1)$ is the value of Z_2 for optimal Z_1, npf - is the required number of Pareto set.

The study models Z_1 and Z_2 as mixed-integer nonlinear programming with non—convex characteristics. Given the complexity of the problem and the need for optimal solutions in real-world scenarios involving small instance problems (13 ports), ensuring optimality is critically relevant for providing meaningful managerial insights. Thus, a state-of-the-art mixed-integer programming solver (CPLEX) was employed due to its robust performance and ability to handle small-scale optimization problems efficiently. As a result, heuristic or approximation methods were not employed, since they do not provide a guarantee of optimality [7]. The dual-objective gap tolerance remained unchanged from its default setting. Computation times varied depending on the corner solutions of the Pareto frontier and across different problem instances: The asymmetric hub port model (AHSN) and the multi-gateway port model- MGPM.

For the multi-gateway port model, this paper analyzes the current scenario where the first destination, e.g., Europe, serves as a transshipment hub for the second destination, e.g., South America. This is compared against the proposed asymmetric hub model, where West Africa functions as a hub center for both destinations. The analysis does not consider scenarios where vessels are deployed individually to connect West Africa with each shipping market (Europe, South America) without utilizing a hub center in West Africa nor in the first destination (e.g., Europe) to connect to the second destination (e.g., South America). Such an approach was demonstrated to be highly expensive and infeasible for a comparative analysis.

5 Results

Figure 3 presents the obtained Pareto set of non-dominated solutions, while Table 1 provides detailed results at the corner points of the Pareto set. Specifically, for $Z_1^*(Z_2)$ – the table shows the optimal value of the objective function (Z_1), its cost components, and the corresponding value of the objective function (Z_2) for optimal (Z_1). Similarly, corner point $Z_2^*(Z_1)$ – shows the optimal value of the objective function (Z_2), its cost components, and the corresponding value of the objective function (Z_1) for optimal (Z_2). Additionally, R_t represents the reliability function, i.e., the probability that a distribution system will operate without failure over a given period t, under specific operational conditions: the geographical context, data, and assumptions used in this study. The reliability is expressed as follows: R_t=1-$e^{-\lambda t}$, where, λ is the instantaneous failure rate, t is the time of interest, and $\lambda = \frac{number\ of\ failures}{total\ operating\ hours}$, [23]. Since the hub system operates as a series network- where the success of the overall system depends on both reliability at the hub and the reliability from the hub to their destination- the overall reliability is given by: $R_t = R_h * R_{hd}$; R_h, $R_{hd} = e^{-\lambda t}$.

At the extreme corner points of the Pareto set, a 60% reduction in Z_1- lease, inventory, late arrival, and vessel daily charter and operating costs- is achieved at the cost of 32% increases in Z_2- emissions, fuel, and port due costs- for a multi-gateway distribution system. This cost tradeoff results in a 62% total system failure probability, highlighting improved reliability on the origin-hub leg (0.83% reliability) but decreased reliability on the hub-destination leg (0.46% reliability). The opportunity cost associated with every 1-unit reduction in Z_1 is -$0.392.

Contrariwise, focusing on minimum Z_2 implies 147% increases in Z_1. However, this cost tradeoff significantly improves reliability on the hub-destination leg (0.61% reliability). Still, it fails to enhance the reliability in an origin-hub leg (0.58% reliability), leading to a 65% total system failure probability. It is important to recall that reliability is evaluated based on the specific operational conditions previously outlined in this study. There are, of course, other factors, such as maintenance frequency and external factors, including weather conditions and health crises (e.g., COVID-19), that affect reliability.

Table 1 Detailed results at the corner points of the Pareto set

$Z_1^*(Z_2)$	Z_1 (10^6 USD)	Z_2 (10^6 USD)	PDC (10^6 USD)	VEC (10^6 USD)	VFC (10^6 USD)	R_h (%)	R_{hd} (%)	R_t (%)	n_k	Avg. speed (knots)
MGPM	6.5039	15.6440	10.6284	0.8563	4.1593	83	46	38	11	25
AHSN	7.6792	11.1725	9.0117	0.3698	1.7918	100	41	41	10	23.7

$Z_2^*(Z_1)$	Z_1 (10^6 USD)	Z_2 (10^6 USD)	VOC	Clease	CINV	LAC	THC	R_h (%)	R_{hd} (%)	R_t (%)	n_k	Av. speed
MGPM	16.0937	11.8821	9.4452	0.8566	1.0999	2.8955	1.7963	58	61	35	6	15
AHSN	13.3143	9.5634	7.6846	0.8692	1.0845	0.7798	2.8960	64	52	33	6	15

Likewise, the opportunity cost associated with every 1-unit reduction in Z_2 is -$2.392. In contrast, for the proposed asymmetric hub distribution system, a 42% reduction in Z_1 requires a 17% increase in Z_2. This tradeoff achieves 100% reliability on the origin-hub leg, whereas reliability on the hub-destination leg falls significantly (0.41% reliability), resulting in a 59% total system failure probability. The opportunity cost associated with every 1-unit reduction in Z_1 is -$0.285. On the other hand, a 14% reduction in Z_2 can be achieved at the expense of a 73% increase in Z_1. This tradeoff results in a 67% total system failure probability, with improved reliability on the origin-hub leg (0.64% reliability) but reduced reliability on the hub-destination leg (0.52% reliability). The opportunity cost associated with every 1-unit reduction in Z_2 is -$3.53.

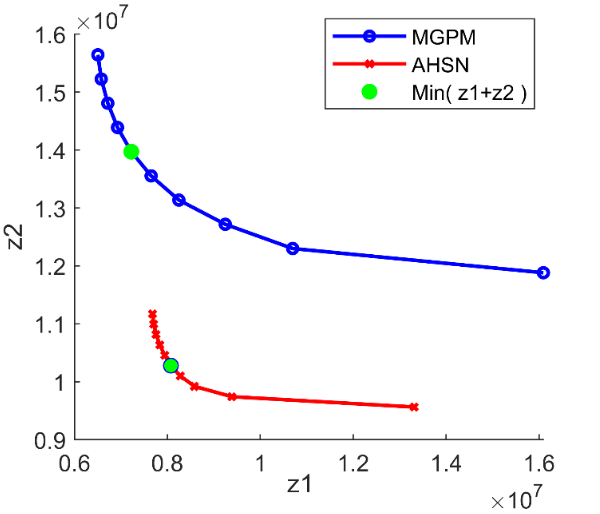


Figure 3 The obtained Pareto set of non-dominated solutions

The obtained Pareto solutions indicate that the proposed asymmetric hub distribution system is strictly better in terms of Z_2 objective (emissions, fuel consumptions, and port due costs), but does not consistently outperform the current multi-gateway distribution system in Z_1. In other words, neither system strictly dominates the other when considering absolute or opportunity costs. The latter finding can be supported by the additional transshipment handling cost/time in a hub system. However, for the minimum generalized cost of routes (Z_1+Z_2) and customer service performance (Figure *4*) the asymmetric hub delivery system remains the superior choice.

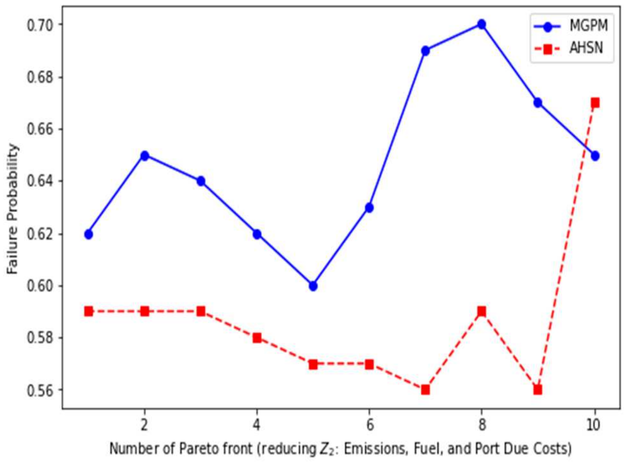


Figure 4 Probability of failure for on-time delivery as Z_2 decreases

5.1 *Sensitivity to the vessel displacement*

Ignoring vessel displacement can lead to significant under-or overestimation of fuel consumption-and consequently emissions- since fuel usage at a given speed varies depending on whether the ship is fully loaded, empty, or partially loaded. However, conventional models in maritime logistics usually assume speed as the primary variable affecting fuel consumption, whereas more recent literature argues that the ship payload constitutes the principal variable. Additionally, the most accurate and realistic approximation of fuel consumption should consider both speed and payload. Thus, the fuel consumption in 6 can be rewritten as follows.

$VFC_{rik} = \frac{f_k (V_{rik})^{n_k - 1}}{24} \cdot \left(\frac{Q_r . w^{Q_r} + w_{lk}}{w_{tk} + w_{lk}}\right)^{2/3}$, Where: w^{Q_r} - is the average container weight (TEU) in a shipping route. w_{lk}-($k \in$ k) is the ship lighweight, and w_{tk} ($k \in$ k) is the ship deadweight.

The results (Figure 5) indicate that, however, the above analysis remains stable, i.e., neither delivery system strictly dominates the other, fuel consumption and emissions were initially overestimated when displacement was ignored. The total fuel cost changes from $1,791,834.523 no displacement scenario to $1,434,964.20 displacement scenario, resulting in an estimation error of $356,870.323, for the asymmetric hub delivery system. Conversely, for the multi-gateway delivery system, the total fuel cost changes from $4,159,352.312 to $3,442,394.565 leading to an estimation error of $716,957.747. These findings highlight the importance of accounting for vessel displacement in fuel cost estimations. As shown, the estimation error in a multi-gateway port model is significantly higher; however, the asymmetric hub system remains more fuel-efficient.

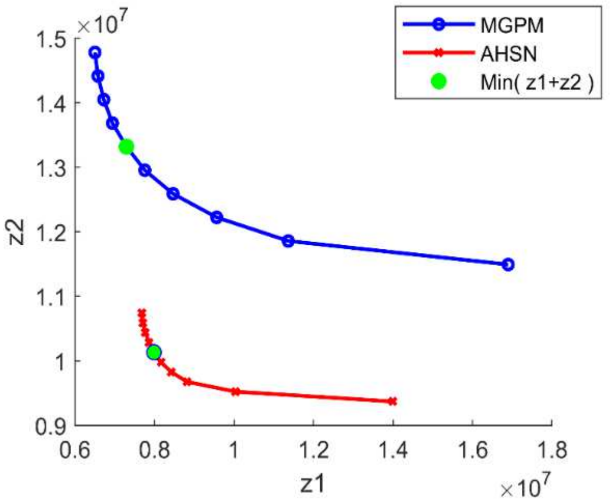


Figure 5 The obtained Pareto set of non-dominated solutions for the sensitivity analysis to vessel displacement

5.2 Sensitivity to growth in market demand

This section evaluates the impact of increasing logistics services demand on the effectiveness of the asymmetric hub delivery system compared to the multi-gateway port system. While the multi-gateway port enables more balanced cargo distribution, the hub system relies on cargo consolidation, which increases vessel displacement and associated inefficiencies. To explore this, the paper simulates higher cargo volumes based on data from major neighboring hub ports such as Algeciras. The port of Algeciras handled approximately 4.77 million TEUs in 2022 (according to multiple sources, including Statista), more than three times the cargo volume used in the initial analysis. To allocate the increased cargo volume across ports, the current demand share of each port was used. For example, the port of Abidjan, which accounts for 13% of the current demand, was allocated 13% of the 4.77 million TEUs. The obtained Pareto solutions (Figure 6) reveal that as logistics demand grows, the multi-gateway port model strictly dominates the asymmetric hub system. In other words, the multi-gateway port model is significantly better in both $Z_1$and Z_2 objective functions.

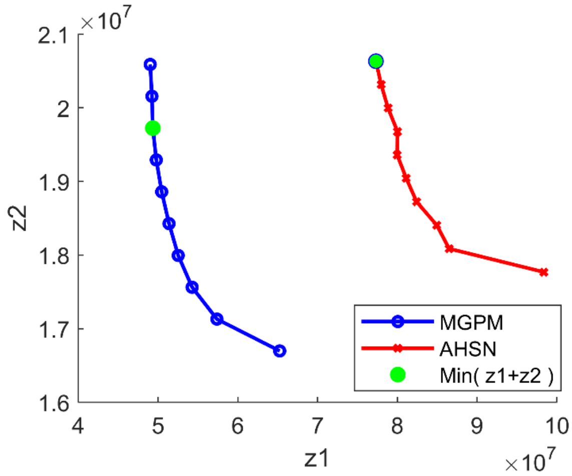


Figure 6-the obtained Pareto set of non-dominated solutions for the sensitivity analysis to growth in market demand

However, managing an extensive costliness with several operational ports such as West Africa, through a single hup becomes increasingly challenging in a growth market. To address this, the insertion of an additional transshipment/getaway hub i.e., a strategic decentralization of the hub system is considered. Supply chain management research emphasizes cargo volume as a key factor in hub selection. In West Africa, ports such as Abidjan, Tema, and Lagos handle the highest cargo volumes. This paper evaluates the impact of adding Tema as an additional hub/gateway to support the centralized hub in a growth scenario. To account for the cargo volume each hub can attract and compute transshipment costs/time/TEU, the following constraints are introduced. q_c+q_s+=$\sum_{i,j \in P} \sum_{k \in K} d_{i,j,k}$, $i \neq j$ (the sum of cargo received at central and secondary hubs/gateway equals the total cargo transported from all origins to all destinations using specific ship type), $d_{i,j,k}$=$q_i . x_{i,j,k}$ $\forall i, j \in$ P,$k \in K$, $i \neq j$ (cargo allocation), $\sum_{i,j \in P} \sum_{k \in K} d_{i,j,k}$ $=q_i$, $\forall i \in$ P, $i \neq j$ (cargo conservation at origin ports), q_c=$\sum_{i,j \in P} \sum_{k \in K} d_{i,j,k}$, $i \neq j$, and $j \neq$secondary hub/getaway (the constraint computes cargo received at the central hub).

The obtained Pareto solutions (Figure 7) indicate that decentralized hubs – rather than de-hubbing- can be a more effective strategy in high-growth markets (around 4 million TEU annually). As can be seen, the hub is strictly better in Z_2 and just as good in Z_1. These findings align with the existing literature that advocates for a shift away from hub-based systems in high-growth markets (de-hubbing), however, extends it by showing that under high demand for logistics services, such decentralization yields superior performance.

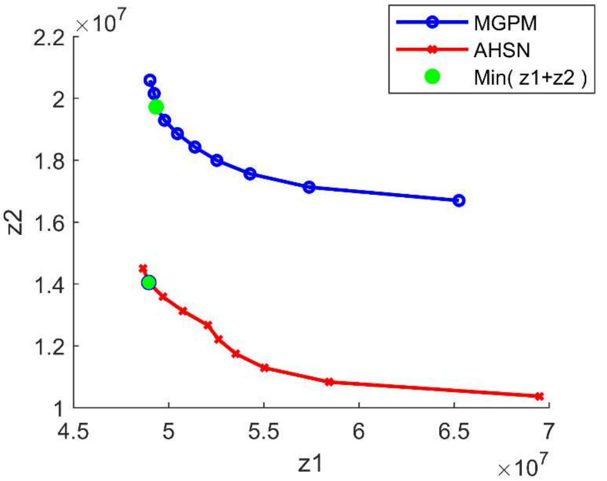


Figure 7 The obtained Pareto set of non-dominated solutions for the sensitivity analysis of additional hub/gateway in a growth market demand

6 Discussion

The proposed multi-criteria optimization approach shows a clear conflicting correlation between emissions reductions, fuel efficiency, and liner tactical choices in route, speed, number, and type of vessel selections, contrasting on-time/ cost performance. The latter finding predicts liner support for a 66% probability of failure for on-time delivery, whereas the opposite is true, that is, reduce failure for high pollution or energy cost. Stated somewhat more specifically, in both systems, liners were required to deploy an average of six (6) vessels and operate at a minimum sailing speed of 15 knots to achieve the lowest Z_2(emissions, fuel consumptions, and port due costs), in turn, the probability of on-time delivery failure was, on average, 66%. To improve customer service performance, liners were required to increase the number of vessels to up to 10 units and raise the average sailing speed to 24.35 knots. Nevertheless, due to high transshipment time (in an asymmetric hub system) and the leg length of the hub-destination (in the traditional multi-getaway system), the failure probability remained high at an average of 60%, that is, a 6% point improvement in customer service performance for an average of 24.5% increases in Z_2(emissions, fuel, and port due costs).

Given these goal conflicts, the results reveal a clear macro-level tradeoff between hubbing and de-hubing strategies, suggesting that West Africa is better off an asymmetric hub system-particularly under relatively low demand for logistics services. Specifically, the hub system proves more efficient in minimizing the generalized cost of routes (Z_1+Z_2) and the associated probabilities of on-time delivery failure. However, in a high-growth market, the centralized hub system becomes inefficient compared to the multi-gateway port system, performing worst in bot Z_1 and Z_2. This outcome supports either a de-hubbing strategy-consistent with the findings of [24] or the insertion of an additional transshipment/gateway hub, i.e., a strategic decentralization of the hub system. Our findings, which extend prior research, show that under high demand for logistics services, such decentralization yields superior performance- achieving better results in Z_2 while maintaining comparable performance in Z_1.

Numerical experiments also reveal that ignoring vessel displacement in fuel cost and emissions estimations leads to significantly greater overestimations in a multi-gateway delivery system compared to a hub system. These findings highlight the importance of aligning logistical network design with a multi-objective optimization approach and the vessel displacement factor.

Implications

The findings of this study have some important implications for policymakers, liners, and further researchers. First, the results show that adopting an asymmetric hub-port strategy in West Africa can reduce logistics costs while enhancing customer-service performance and environmental sustainability along the transatlantic supply chain. Policymakers should therefore prioritize investment in strategic hub infrastructure. Second, shipping lines may benefit from redesigning their network to incorporate a hub-based system, striking a more efficient balance among otherwise conflicting goals. Moreover, the bi-objective modeling framework presented here provides valuable managerial insight by enabling carriers to select Pareto-optimal solutions that best fit their strategic priorities.

7 Conclusion

Logistics service costs have steadily increased over the last few years, with the African region facing the highest logistics costs globally. These high costs directly impact the price competitiveness of African goods and contribute to significant export losses.

Supply chain management literature and practice emphasize cargo consolidation via hub ports as a viable strategy to reduce logistics costs through economies of scale. Aware, the West African governments are willing to transform their ports into logistics hubs for international trade via large-scale investment programs. Given its extensive costliness with multiple operational ports, improving delivery system efficiency is important to reduce logistics costs, enhance trade flows, and drive economic growth.

However, few studies have investigated the role of West African ports as a hub center in the transatlantic supply chain, and even fewer have analyzed the goal conflicts in liner shipping in the transatlantic logistics network. This paper examines the effectiveness of West African ports as a hub center on the transatlantic maritime crossroads and proposes an asymmetric hub system linking West Africa, Europe, and South America. Employing a multi-objective optimization approach based on the e-constraint method, it compares the efficiency of a hub delivery system against the traditional multiple-gateway port system in West Africa. To improve computational efficiency, the original nonlinear fuel consumption function is linearized using speed discretization.

The proposed multi-criteria optimization approach provides practical contributions to maritime logistics and supply chain management within transatlantic logistics. The results here show the conflicting empirical correlation between emissions, fuel efficiency, and the liners tactical decision in route, speed, number, and type of vessel selections, contrasting on-time/ cost performance. The latter finding predicts liner support for a 66% probability of failure for on-time delivery under energy efficiency scenarios, whereas the opposite is true, that is, improving customer service for high energy cost.

Given these goal conflicts, the results reveal a clear macro-level tradeoff between hubbing and de-hubing strategies, suggesting that West Africa is better off an asymmetric hub system, especially under relatively lower demand levels. However, under high demand for logistics services, the insertion of an additional transshipment/getaway hub i.e., strategic decentralization of the hub system may be required to maintain efficiency.

Sensitivity analysis on vessel displacement reveals that ignoring displacement results in a greater overestimation of emissions and vessel fuel efficiency in a multi-gateway system compared to an asymmetric hub system. Future research should focus on the effectiveness of a hub under high demand for logistics services, with an emphasis on strategic collaboration between neighboring hubs and efficient cargo handling.

Limitations

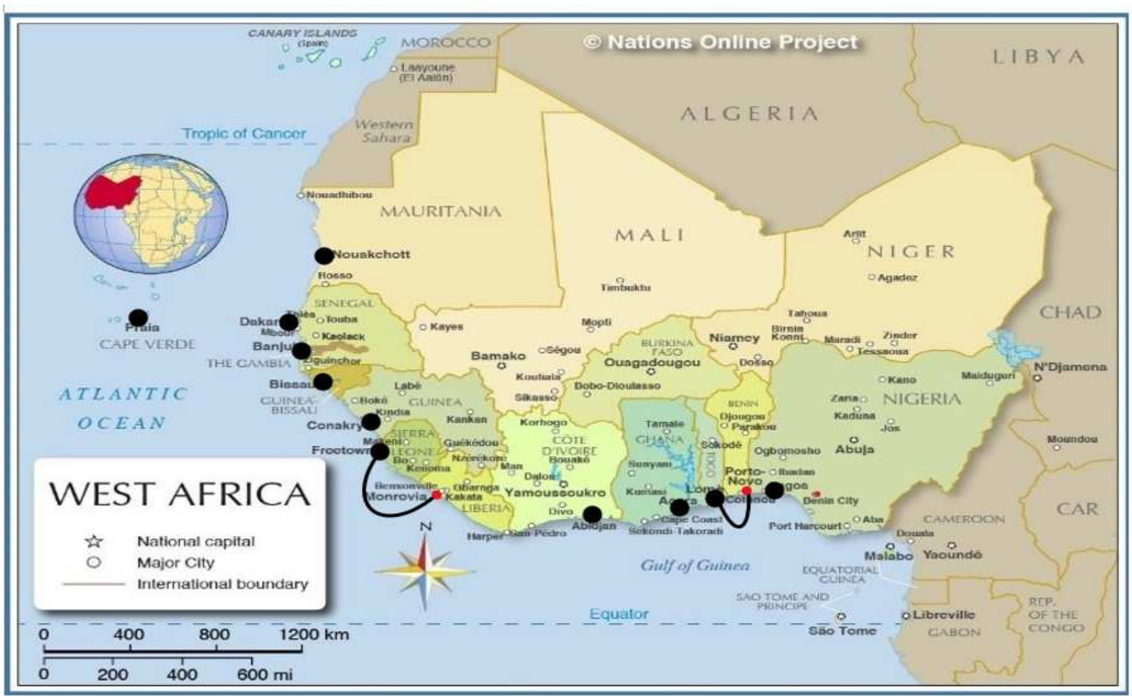
Although this study aims to provide a comprehensive analysis based on real market data, some simplifying assumptions were made to address data limitations. Specifically, handling time in the asymmetric hub system was estimated using yearly container throughput and the average port stay for container vessels (leading to an approximation of 99 TEU/hr.). Conversely, in the multi-gateway port model, where the port of Algeciras serves as a hub for both West Africa and South America, a handling productivity of 200 TEU/hr. was assumed.

Furthermore, as demand for logistics services grows and investment programs expand West African port infrastructure, it was assumed that handling productivity would converge toward levels observed in Algeciras. This assumption reflects: (a) Ongoing port expansion described in the introduction section; and (b) the growing market should follow infrastructure development to resolve bottlenecks and reduce customer dissatisfactions that would eventually slow down growth.

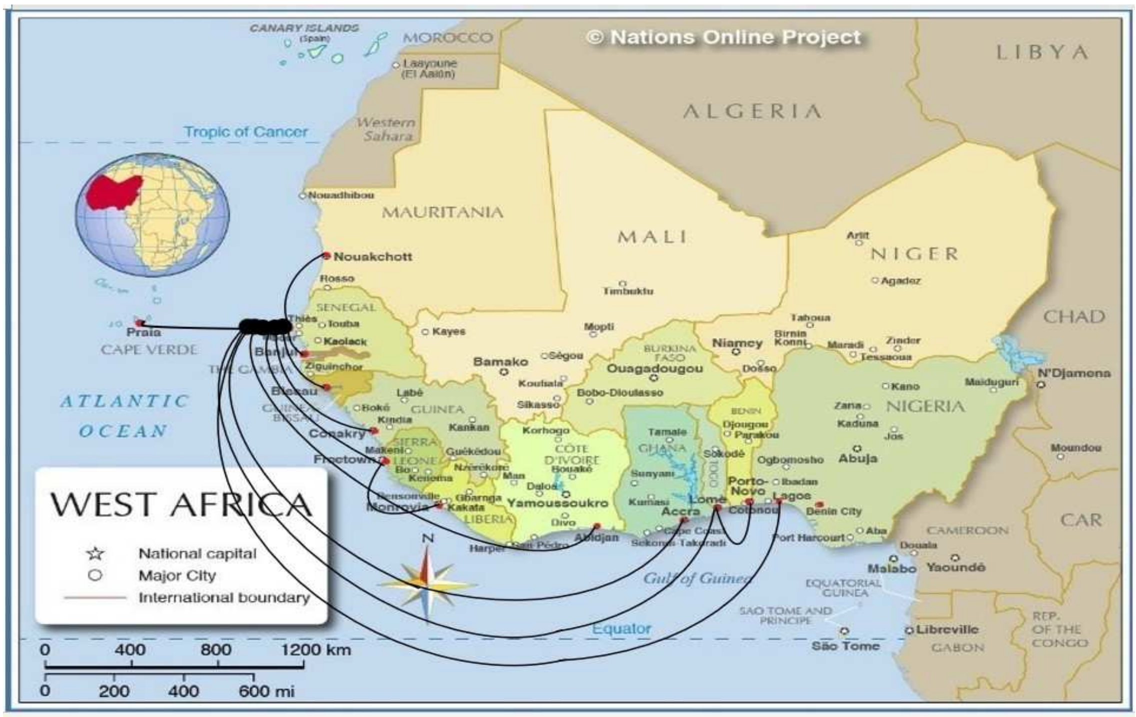
However, this paper acknowledges that real-world port operations face variability due to berth congestion which was not considered in both systems. Further studies may model port congestion and evaluate whether the solution in this study are stable under such a scenario.

Appendix A

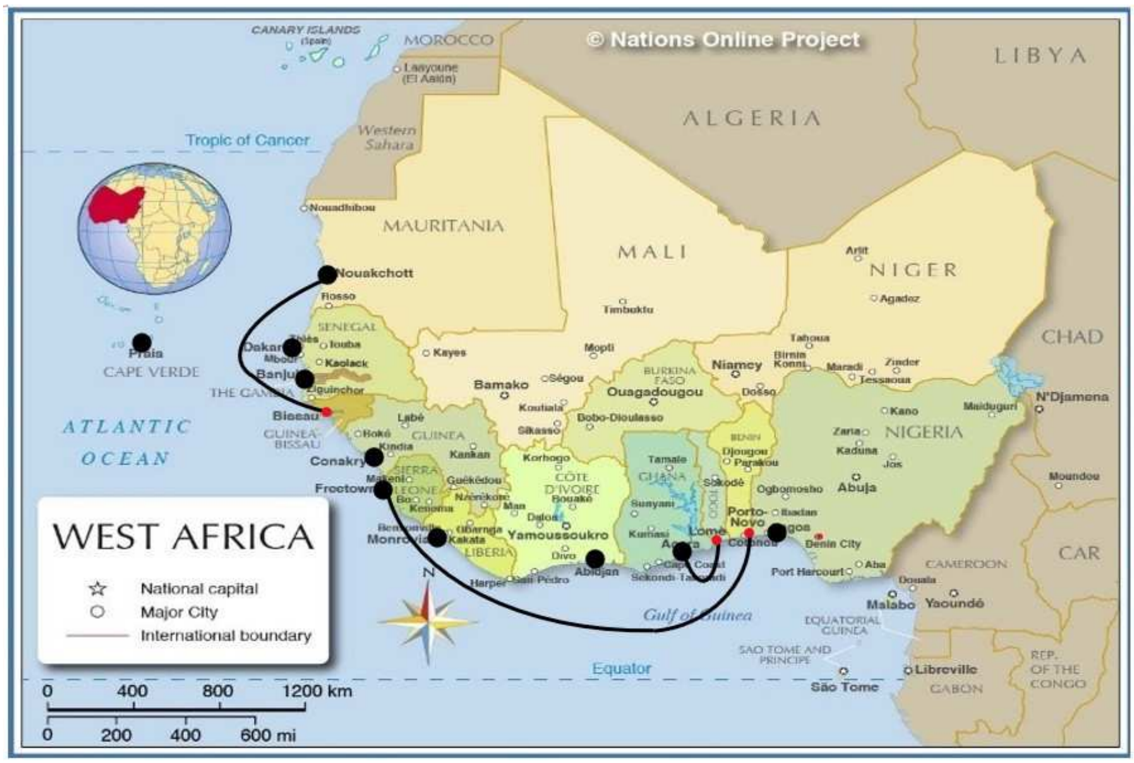
Optimal shipping routes with the minimun generalized costs of routes for different problem instances (A01, A02, A03, A04).



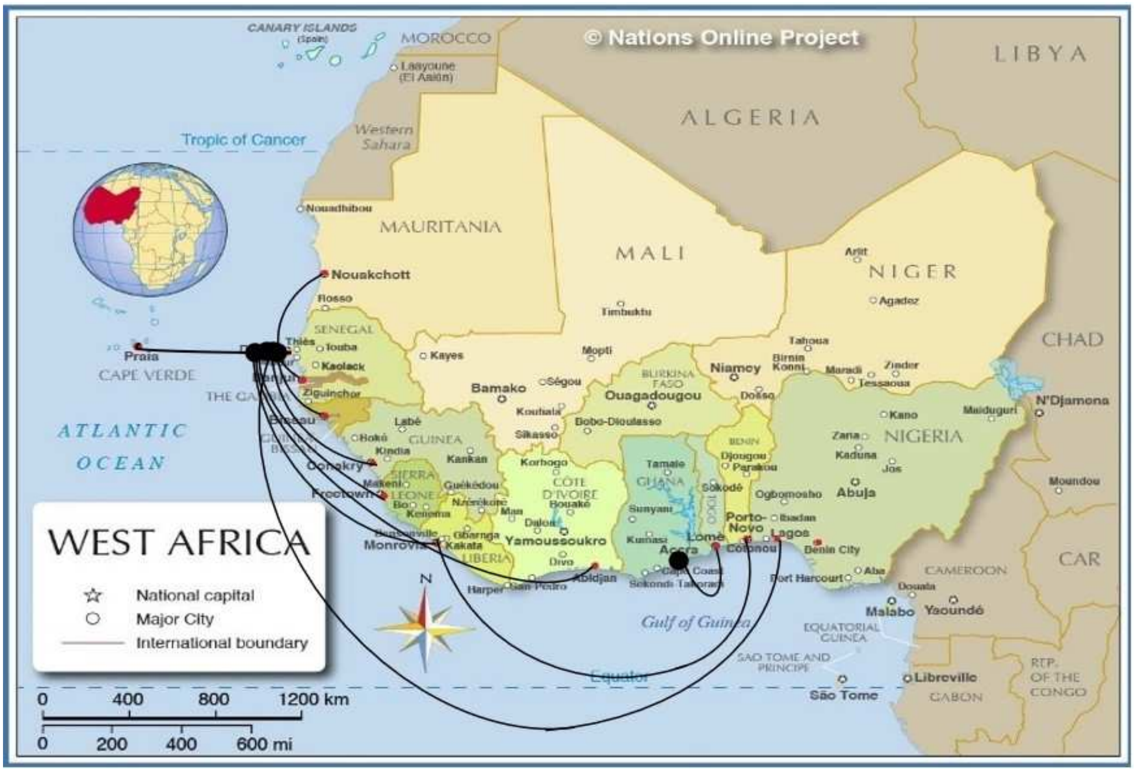
A71 Optimal multi-getaway configuration with the minimum generalized costs of routes (Z_1+Z_2)



A72 Optimal Hub and Spoke network with the minimum generalized cost of routes (Z_1+Z_2)



A73 Optimal Multi-Getaway configuration with the minimum generalized costs of routes (Z_1+Z_2) under a growing demand scenario



A74 Optimal Hub and Spoke network with the minimum generalized cost of routes (Z_1+Z_2) under a growing demand scenario

Note that these routes are derived from specific problem instances and are endogenous to the model.

Appendix B

Some selected real-world imput data for model calibrations (B01, B02).

B01 Terminal handling charge (US\$), and average port time (Pt_{ri}/day)

Ports	$THCp$	Pt_{ri}/Day
Port of Abidjan	130	1.2
Port of Conakry	86	1.9
Port of Freetown	215	0.9
Port of Monrovia	140	1.8
Port of Cotonou	89	0.9
Port of Nouakchott	155	2.1
Bissau port	259	4.8
Port of Lomé	154	1.1
Port of Lagos	187	3.8
Port of Tema	120	1.1
Port of Banjul	105	4.8
Port of Dakar	122	0.8
Port of Praia	82	1.1

In some countries, the absence of port dues cost (mooring, pilotage in/out, and towage) was addressed by adopting costs from their closest strategic ports for simplifications. Moreover, for ports such as Abidjan and Dakar, these costs were adapted from [19] and thereafter aligned with those of their nearest strategic counterparts (B02).

B02 Regression equation for each port for vessel mooring, pilotage and towage

PORTS	$\mathbf{slope_i}$	$\mathbf{Intercept_i}$	$\mathbf{R^2}$
Port of Abidjan	4.0967	5002.044	0.9996
port of Conakry	0.3753	6141.400	0.9919
Port of Freetown	0.3753	6141.400	0.9919
Port of Monrovia	0.3753	6141.400	0.9919
Port of Cotonou	0.2107	686.450	0.9987
Port of Nouakchott	4.0967	5002.044	0.9996
Bissau Port	4.0967	5002.044	0.9996
Port of Lomé	0.2107	686.450	0.9987
Port of Lagos	4.0967	5002.044	0.9996
Port of Tema	0.2199	5916.500	0.9903
Port of Banjul	4.0967	5002.044	0.9996
Port of Dakar	4.0967	5002.044	0.9996
Port of Praia	0.0477	766.690	0.9985

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Review process

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