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Hub Port Cooperation vs Competition: A Multi-Criteria Approach for Cost, Reliability, and Sustainability in Liner Shipping

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Abstract

Efficient logistical services are usually reliable, i.e., they are available when required. However, reliable logistics service is normally inversely proportional to unreliability, implying a cost-tradeoff. Moreover, containerized liner shipping, in particular, relies heavily on port infrastructures and their managerial decision. This paper examines how cooperative vs. competitive strategies between hub ports can affect the design of a logistical network that is cost-effective and reliable. A multi-objective mixed integer nonlinear optimization model is proposed. Numerical experiments were conducted within the West Africa-Europe-South America transatlantic supply chain, focusing on West Africa due to its strategic location (Atlantic shipping crossroads and extensive coastline). The results show that cooperative hubs, whether close or far apart, exhibit a complex interplay between absolute cost performance and marginal efficiency. While hubs nearby achieved superior marginal cost tradeoffs, neither closer nor geographically distant cooperative hubs dominated each other in absolute cost performance. However, the results showcased that competition completely dominates cooperation when hubs are located far apart.

Keywords

Liner Shipping, Hubs Cooperative vs. Competitive Strategy, Multi-Objective Optimization, Pareto Front, Network Design Problem, West Africa

1. Introduction

In an increasingly constrained environment characterized by fierce competition, geopolitical and economic uncertainty, and pollution regulations, containerized liner shipping must enhance efficiency to remain competitive. A commonly adopted strategy to mitigate the latter involves consolidating various origin-destination pairs through a transshipment gateway/hub that exploits economies of scale, specifically between hubs. In parallel, the growing market pressure for more reliable logistical services has forced liner shipping to integrate (vertically and horizontally) to gain size and control not only shipping but the entire supply chain activities (Rodriguez, Agrell, Manrique-de-Lara-Penate, & Trujillo, 2022). However, the fundamental characteristic of containerized liner shipping is its heavy dependence on port infrastructures and the managerial decisions of port authorities. Empirical literature emphasizes that port cooperation, rather than competition, generates positive spillover effects that benefit the entire port network within a geographical region (Li & Oh, 2010). For the West African region (**Figure 1**), many ports have undergone large investment programs to achieve regional hub port status. For example, the African Development Bank Group has financed 60 million EUR to construct a new container terminal at the port of Lomé, which will be used for transshipment and inward goods (African Development Bank Group, 2015). Similarly, DP World and the Senegal government agreed on an ambitious 2-phase development project of 1127 billion U$ to reinforce Dakar as a major regional transshipment getaway/hub port to West Africa (Kherallah, 2020). Moreover, many other potential hubs have undergone similar investment campaigns, see: (Africa Container Shipping, 2022). These ports, equipped with adequate infrastructure and strategically located at the Atlantic shipping crossroads between Africa, Europe, and the Americas, share a unique spatial competitive advantage to assume regional hub port status. Such an advantage, however, can easily escalate competition versus cooperation. This, then, justifies the need to better understand how cooperative vs. competitive strategies between hub ports can affect the design of a cost-effective and reliable logistical network in liner shipping. Liner shipping network design encompasses key routing planning decisions and tactical decisions (fleet deployment and scheduling designs). Most of the decisions that must be made by liner shipping at the tactical level in the network design are conflicting. It follows that, providing reliable service at port requires significant capital investment to deploy a certain number of vessels. In parallel, adopting higher vessel speeds has become common in modern consumerism and short life cycle products. Whereas both practices can enhance system reliability, they also increase vessel fuel consumption, emissions, port due costs (pilotage, towage, mooring), and other vessel-related handling costs. Conversely, unreliable service significantly increases shipping time, the associated costs, and customer dissatisfaction. Nonetheless, the existing literature on ports' competitive versus cooperative strategy usually combines conflicting objectives of liner shipping into one objective, thereby limiting the crucial tradeoff analysis. For example, implementing cooperation between ports may, in fact, worsen at least one key objective in liner shipping, and/or improving environmental objectives may require higher sacrifices in delivery reliability. Indeed, combining these objectives into a single one might wrongly inform the decision-makers. To avoid the latter drawback, this paper proposes a bi-objective mixed integer nonlinear optimization model to minimize liner shipping main production costs. The main costs addressed in the literature are then separated into two conflicting groups, following a similar approach in (Dulebenets, 2018): costs that usually decrease with time (unreliability costs), and costs that commonly increase with time (reliability costs). The main purpose is to examine how cooperative versus competitive strategies between hubs can affect logistical network design that is both cost-effective and reliable. The cost-tradeoff is assessed using the e-constraint method. The Pareto dominance concept will also be explored, where cooperation between hubs is considered to dominate competition if it is superior in at least one liner shipping objective and as good in another. Conversely, they are considered non-dominant (i.e., implementing cooperation should worsen liner shipping at least one objective). Numerical experiments were conducted for the West Africa-Europe-South America transatlantic supply chain (see **Figure 2**). The main focus was placed on the West African region due to its geographical characteristics (extensive coastlines and located at the Atlantic shipping crossroads). Ports in this region offer equal spatial competitive advantages to assume regional hub status, triggering competition or cooperation. Furthermore, the maritime supply chain corridor herein is assumed to be served by a single integrated (vertically and horizontally) container shipping company that transports all West Africa-Europe-South America traffic. The central planner assumption simplifies the analysis, allowing a focused examination of the crucial tradeoff between reliability and unreliability costs at the highest level. The port of Algeciras was selected as the representative port for Europe and the port of Santos for South America. The subsequent part of this paper unfolds as follows: The next section discusses relevant literature. The third section presents the optimization model. The data used in this study is detailed in the fourth section, and the fifth is the solution approach and analysis. Moreover, the final section presents the conclusion of the study.

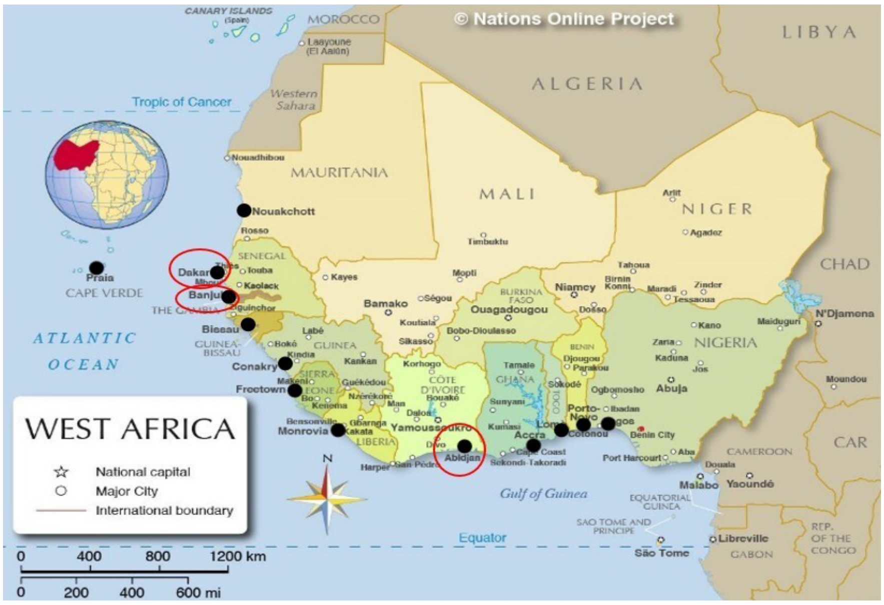

Figure 1. West African countries, with dots representing operational ports and circles indicating potential hub ports. Source: (Nations Online Project, 2023).

Figure 2. Example of a West Africa-Europe-South America transatlantic supply chain, illustrating routes under hub port cooperation (red lines) vs. competition (black lines).

2. Literature Review

Two streams of literature are important to the purpose of this study. 1) liner shipping network design problems; and 2) collaborative versus competitive strategy among ports.

Liner shipping network design problems encompass key decision-making areas, including routing planning, fleet management, and schedule design. Literature concerning liner routing and scheduling has been reviewed by (Meng, Wang, Andersson, & Thun, 2014) with a focus on mathematical model formulations, algorithm design, and assumptions. In addition, studies on containership fleet size, network design (strategic level), service frequency, fleet management, schedule designs (tactical level), and container booking and routing and ship rescheduling (operational level) were thoroughly revised. The study further identifies key areas for research, including but not limited to delivery reliability and environmental sustainability.

The liner shipping decisions, made at tactical or operational levels, often conflict, as discussed earlier. However, most conventional models in the literature typically combine the conflicting objectives into a single one, with only a few attempts to capture the conflicting nature between the liner's main production costs, and they will be revised here.

Dulebenets (2018) Proposed a global multi-objective optimization algorithm based on the e-constraints method to solve the conflicting vessel schedule (tactical level) problems. Numerical experiments were conducted for the Asia-Mediterranean liner shipping route. Results of sensitive analysis reveal that vessel schedules are more sensitive to a unit fuel cost change than unit emission cost. Rodriguez, Agrell, Manrique-de-Lara-Penate, & Trujillo (2022) proposes a bi-objective based on a weighting method for fleet deployment cost (tactical decisions), time, and emissions. The authors aimed to find a tradeoff between pure cost and time minimizations and cost and emissions. They highlighted that cost reductions could be attained through an increase in transportation time/cost. Wen, Chen, Yin, Lau, & Dulebenets (2024) proposed a multi-objective for green shipping scheduling (tactical decisions) to minimize costs, carbon emissions, and service unreliability. Results indicated that congested port's effects on service unreliability are greater than additional costs and emissions. Elmi et al. (2023) focused on the vessel schedule recovery problem and proposed a multi-objective model based on an e-constraint method aimed to minimize the total ships late arrival cost and minimize total profit loss in a potentially disruptive event at the port. Numerical experiments were conducted for the Europe-Pakistan-India shipping route. The results indicated that the model proposed is able to generate Pareto sets in a timely manner.

Ports Cooperative vs Competitive Strategy

Ports along the same extensive geographical coastlines may equally share opportunities to become regional hub ports, thereby intensifying competition to attract customers. However, cooperation is a significant strategy to enhance overall port competitiveness and crowd out competitors/competitions. The primary rationale is that cooperation between ports can facilitate and enhance integrations within the supply chain network, mitigate disruptions, alleviate congestions, provide greater flexibility in the liner routing planning, resulting in cost reductions, and stimulate regional economic growth (Lezhnina & Balykina, 2021). For example, (Munim & Haralambides, 2018) studied competition and cooperation for intermodal container transshipment between Bangladesh and Indian ports. A mixed integer linear optimization model was proposed for port user cost reductions and port transshipment revenue. Numerical experiments showcased that port users could highly benefit from cooperation in terms of cost reductions. Similarly, (Trujillo, Campos, & Pérez, 2018) developed a case study for Chile cooperative versus competitive strategy between neighboring ports and concluded that cooperation would lead to growth. (Li & Oh, 2010) research competition versus collaborations between Shanghai Port and Ningbo-Zhoushan Port. The results suggested that the two ports should avoid competition to generate positive spillover effects for the entire port network within the Yangtze River Delta region. For a similar study, refer to: (Saeed & Larsen, 2010).

Studies focused on port cooperative vs competitive strategy have not evaluated their effects on conflicting objectives in liner shipping, which, in turn, causes limitations in the analysis of crucial tradeoffs. Further research is required on how cooperative vs. competitive strategies between hubs can affect the design of a logistical network that is cost-effective and reliable throughout the West Africa-Europe-South America transatlantic supply chain. Therefore, although the existing literature offers valuable practical managerial insights, it cannot directly be used to inform stakeholders within this paper study area. Thus, this study contributes to both literature and supply chain management practice.

3. Optimization Model

The study proposes a mixed integer nonlinear mathematical model to minimize liner shipping main weekly route production costs addressed in the literature and separate them into two conflicting groups: Z_1-costs that typically decrease with time: 1) port due cost (PDC), 2) vessel emission cost in the sea (VEC), 3) vessel fuel consumption cost (VFC), 4) terminal handling cost (THC) (as a weighting cost), and Z_2-costs that commonly increases with time; 5) vessel daily charter and operating cost (VOC), 6) container lease cost in sea as well as at ports ($Clease$), 7) cos of inventory in sea as well as at ports ($CINV$); 8) vessel late arrival cost (LAC); 9) vessel handling cost at ports (VHC). All the formulas used to compute each cost component for each objective were adapted from (Correia & Chengji, 2024).

Nomenclature

Sets

$P=\{1,2,\cdots,n_p\}$ set of port of call;

$K=\{1,2,\cdots,n_k\}$ set of available ship's (ship types);

$H_p=\{1,2,\cdots,n_{H_p}\}$ set of hub port.

Binary variable

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

Auxiliary variables

t_{ik} arrival time (hr.) of ship k at pot i;

w_{ijk} travel time (hr.) 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;

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

tc_{hk} transshipment time at the hub port h;

V_{rik} ship sailing speed (knots);

SL_i slope for the equation of simple linear regression to approximate the port due cost/vessel handling costs at port i;

in_j intercept for the equation of simple linear regression to approximate the port due cost/vessel handling costs at port i;

Pt_i port time at port i (hr./day);

Q total amount of containers (TEU);

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

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);

LOA vessel length overall;

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

α_1 capital cost parameter (USD);

α_2 factor modeling the effect of economies of scale due the vessel size, $0 < \alpha_2 \le 1$;

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

vfc vessel fuel consumption;

c^{ivt} the unit inventory cost (USD/hour.

$$\begin{aligned} Z_1 = {} & \sum\nolimits_{i,j\in P}\sum\nolimits_{k\in K} SL_j * Cap_k + in_j * x_{ijk} + \sum\nolimits_{i,j\in P}\sum\nolimits_{k\in K} q_j * c_j^{hand} * x_{ijk} \\ & + \sum\nolimits_{i\in P} q_i \sum\nolimits_{k\in K} \sum\nolimits_{j\in P, j\neq i, j\neq h} x_{ijk} \cdot c_h^{hand} \\ & + \sum\nolimits_{i,j\in P}\sum\nolimits_{k\in K} \left(ef * ecp * dis_{ij} * x_{ijk} \right) * vfc \\ & + \sum\nolimits_{i,j\in P}\sum\nolimits_{k\in K} \left(fp * dis_{ij} * x_{ijk} \right) * vfc \end{aligned}$$

$$\begin{aligned} Z_2 = {} & \sum\nolimits_{i,j\in P}\sum\nolimits_{k\in K} \frac{\alpha_1 * Cap_k^{\alpha_2}}{24} * w_{ijk+tc_{hk}} + \sum\nolimits_{i,j\in P}\sum\nolimits_{k\in K} \frac{c_r^{lease}}{24} * w_{ijk+tc_{hk}} \\ & + \sum\nolimits_{i,j\in P}\sum\nolimits_{k\in K} c^{ivt} * w_{ijk+tc_{hk}} + \sum\nolimits_{k\in K} \left(lc * tlh_k \right) \\ & + \sum\nolimits_{i,j\in P}\sum\nolimits_{k\in K} SL_j * LOA_k + in_j * x_{ijk} \end{aligned}$$

St.

$$Z_1 \le e_1 \tag{1}$$

$$Z_2 \le e_2 \tag{2}$$

$$\sum\nolimits_{h\in H}\sum\nolimits_{i\in P} x_{ihk} \le 1, \quad \forall k \in K \tag{3}$$

$$\sum\nolimits_{j\in P}\sum\nolimits_{k\in K} x_{ijk} = 1, \quad \forall i \in P, \quad i \neq j \tag{4}$$

$$\sum\nolimits_{j\in P} x_{ijk} - \sum\nolimits_{j\in P} x_{jik} = 0, \quad i \in P, \quad k \in K, \quad i \neq j \tag{5}$$

$$\sum\nolimits_{i\in P} q_i \cdot \sum\nolimits_{j\in P, j\neq i, j\neq h} x_{ijk} \le Cap_k, \quad k \in K \tag{6}$$

$$\sum\nolimits_{i\in P} q_i \cdot \sum\nolimits_{j\in P, j\neq i, j\neq h} x_{ijk} \le Cap_k + M\left(1 - y_{hjk}\right) \tag{7}$$

$$\sum\nolimits_{k\in K} Y_{hjk} \ge 1, \quad \forall j \in P \tag{8}$$

$$\sum\nolimits_{j\in P}\sum\nolimits_{k\in K} q_j \cdot y_{hjk} \ge \sum\nolimits_{j\in P} q_j \tag{9}$$

$$t_{hk} \ge 168, \quad \forall k \in K \tag{10}$$

$$tlh_k \ge t_{hk} - 168 - M_1\left(1 - x_{ihk}\right), \quad \forall k \in K, \quad i \in P, \quad h \in H_p \tag{11}$$

$$t_{ik} + Pt_i + dis_{ij} * \frac{1}{V_{rik}} - t_{jk} \le M_1\left(1 - x_{ijk}\right), \quad \forall k \in K, \quad i, j \in P, \quad i \neq j, \quad i \neq h \tag{12}$$

$$\begin{gathered} w_{ijk} + M_2\left(1 - x_{ijk}\right) \ge \left(t_{jk} - t_{ik}\right) * q_i - M_2\left(1 - z_{ijk}\right) \\ \forall k \in K, \; i, j \in P, \; i \neq j, \; i \neq h \end{gathered} \tag{13}$$

$$\begin{gathered} w_{ihk} + M_2\left(1 - x_{ijk}\right) \ge \left(t_{hk} * q_i\right) - M_2\left(1 - z_{ijk}\right) \\ \forall k \in K, \; i, j \in P, \; h \in H_p, \; i \neq j, \; j \neq h \end{gathered} \tag{14}$$

$$x_{ijk} \le z_{ijk}, \quad \forall k \in K, \quad i, j \in P, \quad i \ne j \tag{15}$$

$$x_{ijk} \ge z_{ijk} - 1, \quad \forall k \in K, \quad i, j \in P, \quad i \ne j \tag{16}$$

$$x_{ihk}, y_{hjk} \in \{0,1\}, \quad \forall k \in K, \quad i, j \in P, \quad h \in H_p \tag{17}$$

$$V_{rik} Q, \quad q_j \in N \tag{18}$$

$$lc, ef, dis_{ij}, tlh_k, Pt_i, tc_{hk}, ecp, c_j^{hand}, t_{jk}, w_{ijk}, sf_j \in R^+ \tag{19}$$

Constraints 1 and 2 bound the objective functions to an epsilon value whenever at least one objective is being solved, and the other is regarded as a constraint. Constraints set 2 - 5 are commonly used to generate the vessel's shortest path. Constraints set 6 - 7 are the vessel capacity constraints, ensuring the number of containers transported will be at most the vessel capacity. Constraint 8 limits the number of vessels in the main route, while constraint 9 ensures that all the cargo is delivered to its final destination. Constraint 10 defines the time window constraint, where 168 refers to the hours in one week. Constraint 11 is a late array. Constraints set 12 - 16 compute the vessel transit time, and the parameter (TEU/time) expresses the product of the total number of containers on board times the total sailing time in a path. Given that the sailing time between origin-destination in this study area does not take more than 8 weeks, the strict bounds for M_1, M_2 can be estimated as follows: $M_1 = 8$ weeks*168/h week, $M_2 = M_1 * \sum_{j \in P} q_j$. The constraints set 17 - 19 demonstrate the nature of parameters and variables.

4. Data Specifications

For the purpose of analysis, real port and market data were collected from various sources, including previous literature, port authorities, and statistical agencies. The container trade volume (TEU) between origin-destination pairs, the port dues costs, the container handling charges, and port time were retrieved from (Correia & Chengji, 2024); see **Table A1**, **Table A2** & **Table A3** (Appendix A). The vessel handling cost (berth) was obtained from the port authority, whereas the vessel information (TEU, Gt_k—gross tonnage, LOA—length overall, and speed) was obtained from the Marine Traffic and Hapag-Lloyd websites, and the vessels parameters, such as a_k and g_k were estimated following (Koza, 2019; Correia & Chengji, 2024) as displayed in **Table A4** (see Appendix A). The nautical distance (nmi) between the respective ports was obtained from searates. Furthermore, The late arrival cost parameter is set at 5000 US$/hr., the emission cost parameter at 32 US$, the emission factor at sea is set at 3.114, while fuel consumptions coefficients is set at— $f_k = 0.012$ and $\underline{n}_k = 3.0$, the inventory cost was set to- $c^{ivt} = 0.25$ US$/hour/TEU, following (Pasha, et al., 2022; Rodriguez, Agrell, Manrique-de-Lara-Penate, & Trujillo, 2022). The fuel price is assumed to be 484 US$ per ton, and the vessel charter cost parameter (USD) for the vessels daily charter and operating costs is set as follows— α_1 is set at 300 US$/day· ton$^{\alpha_2}$, $\alpha_2 = 0.6257$, moreover the container lease cost is set at US$4.5/TEU/day following (Tu, Adiputranto, Fu, & Li, 2018; Kim, Lam, & Lee, 2018; Correia & Chengji, 2024).

The average transshipment time is set as follows, $tc_{hk} = \frac{\sum q_i}{ht}$, $\forall h \in H_p$, ht—is the average container handling productivity at hub port assumed to be [75; 100; 120; 130] TEU/hr.

5. Solutions Approach and Analysis

Since the proposed model is bi-objective, there exists a set of optimal solutions that constitute the pareto front. In the context of multi-objective optimization, the Pareto Front represents a set of non-dominant solutions, where improving one objective can only be accomplished at the expense of worsening the other objectives. Several techniques have been suggested to solve multi-objective and constitute the Pareto Front. This study adopted the epsilon constraint method to address the proposed bi-objective problem due to its effectiveness in handling real-world non-convex functions. Specifically, one objective is treated as the primary objective while the other is designated as a constraint.

Furthermore, the Pareto Front is constructed by adjusting the epsilon value on the constrained objective. This, then, requires a priori that the epsilon upper bound interval is determined as follows: $e = \frac{Z_2(1) - Z_2^*(Z_1)}{npf - 1}$; 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 desired number of Pareto Front. Both objective functions in this study are modeled as mixed-integer nonlinear and non-convex problems. Given the complexity and the need for optimal solutions in real-world scenarios involving 12 ports, ensuring optimality is crucial for effective managerial decision-making. To achieve this, this study opted to use a commercial mixed-integer programming solver (CPLEX) specifically designed to guarantee optimality. As a result, heuristic or approximate algorithms were not applied, as they may not provide optimal solutions (Dulebenets, 2018). The dual objective gap tolerance was set to default. The computation time varies at the corner points of the Pareto Front and across different instances of problems, organized as follows: 1) a single hub port of Dakar is placed within the West African region (HSN); 2) two cooperative hub port are placed and located closed together (hub port of Dakar and Banjul—HSNP); 3) Two cooperative hubs are placed and located farther apart, (hub port of Dakar and Abidjan—HSNA); For a cooperative agreement between two hubs, the transshipment handling cost was standardized as follows: $THC_h = \frac{c_{h \in H_1}^{hand} + c_{h \in H_2}^{hand}}{2}$, $c_{h \in H_1}^{hand}$, $c_{h \in H_2}^{hand}$ is the container handling charge at hub port 1 and 2. Furthermore, port due costs (pilotage, towage, mooring) and transshipment handling time are assumed to be the same under the cooperative strategy. For hubs located close together, the cooperation is at the regional level, and only one acts as a getaway. The reason behind these assumptions is that both cooperative hubs located farther apart are larger hub ports with enough capacity to handle higher vessels, negating the need for just one to act as a getaway.

Conversely, for hub ports close together, only one (Dakar) has adequate infrastructure for larger vessels. However, a sensitivity analysis is conducted to account for the change in the levels of cooperation: 1) hub ports cooperating only in transshipment costs; 2) both cooperative hubs located close together acting as getaways.

The selections for the hub ports of Abidjan and Dakar are based on the empirical literature, indicating them as the best locations for a hub port within the West African region (Dyck & Ismael, 2015; Correia & Chengji, 2024). In contrast, the port of Banjul is due to its proximity (90.49/nmi apart from Dakar). **Figure 3** shows the obtained set of non-dominant solutions, whereas **Table 1** illustrates the results at the corner points of the Pareto Front. that is, $Z_1^*(Z_2)$—the optimal value of the objective function (Z_1), its costs components, and the value of the objective function (Z_2) for optimal (Z_1). similarly, corner point $Z_2^*(Z_1)$—the optimal value of the objective function (Z_2), its costs components, the value of the objective function (Z_1) for optimal (Z_2), and R_t, probability that a system will operate without failure in a given period of time *t*, under specific operational conditions: 1) scenarios, hub ports cooperation vs. competition; 2) data used in this paper. $R_t = 1 - e^{-\lambda t}$, λ is the failure rate, *t* is the time of interest, and $\lambda = \dfrac{\text{number of failures}}{\text{total operating hours}}$ (Blanchard, 2014).

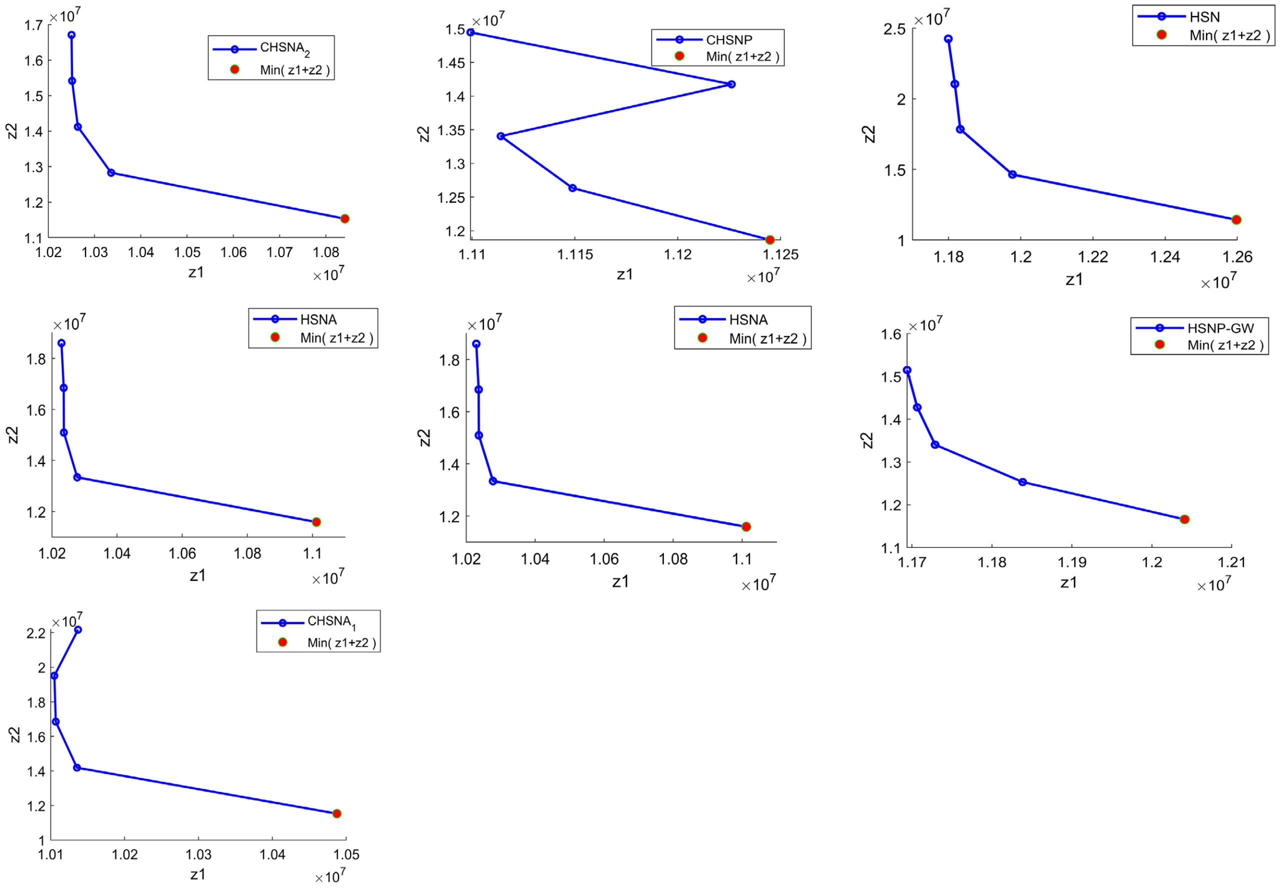

Figure 3. Set of non-dominant solutions.

Table 1. Solutions at the corner points of the Pareto Front.

$Z_1^*(Z_2)$	z_1	z_2	*THC*	*PDC*	*VEC*	*VFC*	R_t	*n. vessels*	
HSN	1.26e+07	1.14e+07	3.76e+06	8.83e+06	1692.538	7954.023	0.00%	*10*	
HSNP	1.21e+07	1.05e+07	3.32e+06	8.80e+06	1644.074	7718.582	0.00%	10	
HSNA	1.10e+07	1.16e+07	2.39e+06	8.61e+06	1502.644	6903.128	0.00%	10	
$Z_2^*(Z_1)$	z_1	z_2	*VOC*	*Clease*	*CINV*	*LAC*	*VHC*	R_t	*n. vessels*
HSN	1.18e+07	2.42e+07	2.09e+07	1.01e+06	1282335.260	1.05e+06	1034.799	0.53%	4
HSNP	1.17e+07	1.40e+07	1.22e+07	591270.317	730640.423	484803.468	950.168	0.26%	5
HSNA	1.02e+07	1.86e+07	1.64e+07	599603.005	741750.675	887606.535	1988.854	0.39%	7

At the corner points of the Pareto Front, a 7% reduction in unreliability costs (Z_1) can be accomplished at the expense of 61% increases in reliability costs (z_2), for two cooperative hub ports located farther apart. This cost tradeoff results in a 39% chance that the liner shipping will fail to provide reliable logistics service. Conversely, reducing the probability of failure (0%) would require reducing 38% reliability cost at the expense of 8% increases in unreliability costs. Recall that reliability probability is usually measured under specific operational conditions described above for this paper.

In contrast, when two cooperative hub ports are located close together, a 4% reduction in unreliability costs requires a 33% increase in reliability costs, leading to a 26% probability of failure to provide reliable logistics service. Avoiding this failure entirely would mean reducing 25% reliability costs, which, in turn, worsens unreliability costs by 4%.

Similarly, for a single non-cooperative hub, improving unreliability costs by 6% necessitates a significant 112% increase in reliability costs, with a resulting 53% chance of failure if the cost-tradeoff is accepted. Conversely, reducing the failure probability to 0% would demand a 53% reduction in reliability costs at the expense of a 7% increase in unreliability costs.

Cooperation between hub ports located close together demonstrated superior efficiency in marginal cost-tradeoff between the conflicting objectives, particularly when compared with cooperative hub ports located farther apart. The marginal cost-tradeoff from reliability to unreliability is only 8.2%, implying that for every 1% reduction in unreliability costs (such as emissions, fuel consumptions, port due costs, and transshipment handling costs), an 8.2% sacrifice in reliability costs is necessary. This is more favorable than the 8.7% and 18.6% sacrifices required when cooperative hubs are geographically distant or when a single non-cooperative hub strategy is employed, respectively. Conversely, the marginal tradeoff ratio from unreliability to reliability is only 13% for a single non-cooperative hub strategy. This is more advantageous than the 16% and 24% ratios observed when two cooperative hubs are located close or geographically distant, respectively.

However, it's important to note that cooperative hubs, whether located close together or farther apart, are non-dominated with respect to each other in terms of absolute cost performance **Figure 4(a)**, implying that it is impossible to implement either one without worsen at least one of the liner shipping objectives. The non-dominance can be supported by the higher cargo volume from the hub port of Abidjan, which reduces the need for additional transshipment costs and the deployment of extra vessels. However, cooperative hubs located close together strictly dominate the single non-cooperative hub strategy regarding absolute cost performance. In other words, the solution on the Pareto Front for the cooperative hub is significantly better in Z_2 and just as good in Z_1 compared to any corresponding solutions in a single non-cooperative hub strategy, as presented in **Figure 4(b)**. The latter can be extended to a single non-cooperative hub strategy and two geographically distant cooperative hub ports.

Therefore, for liner shipping willing to accept small increases (4%) in unreliability costs (including emissions and fuel costs) to maintain a cost-effective reliable logistics service (0% chance of failure), cooperative hub ports close together offer a significant advantage. On the other hand, cooperative hub ports located farther apart are more beneficial for liner shipping prioritizing sustainable practices, such as reducing emissions and improving vessel energy efficiency within the transatlantic supply chain, and being willing to tolerate a 39% chance of reliable logistics service failures. As shown in **Table 1**, C02 emissions produced at sea are 9% and 13% lower under the cooperative hub's strategy located farther apart compared to cooperative hubs located close together and the single-non-cooperative hub strategy, respectively.

These findings suggest that further alliances and negotiations between liner shipping companies and port authorities could help balance these conflicting objectives, benefiting all stakeholders.

The Competition Effects

This section evaluates the impact of competition between hubs on the logistical network, comparing these results with the cooperative scenarios described earlier. The same scenarios are examined: 1) two competing hub ports located close together (hub port of Dakar and Banjul—CHSNP); and 2) Two competing hubs located farther apart (hub port of Dakar and Abidjan—CHSNA). The resulting Pareto solutions are displayed in **Figure 4**.

The results show that the effects of competition between hubs on a cost-effective and reliable logistics network are highly sensitive to competitive market dynamics. Specifically, the influence depends on which hub has lower costs or time and whether the competition between hub ports is classified as moderate or aggressive.

In this paper, aggressive competition is defined as a scenario where one hub consistently strives to undercut its competitor across multiple areas, offering lower overall port due, transshipment handling costs, and time. Conversely, competition is considered moderate when hub ports offer lower costs in some areas (e.g., transshipment handling time) while maintaining higher costs in others (e.g., port dues and transshipment handling costs).

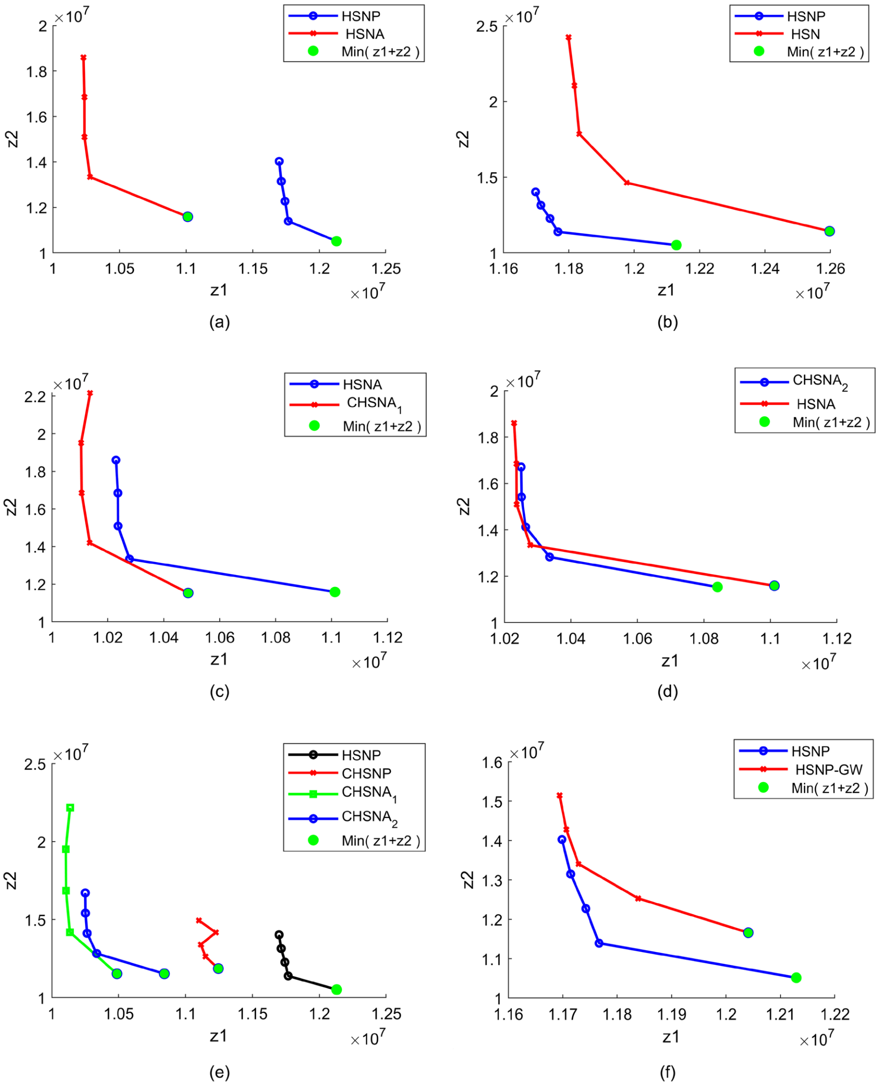

Figure 4. Set of non-dominated and dominated solutions.

The results indicated that when hubs engage in aggressive competition, neither cooperation nor competition dominates the other, **Figure 4(c)**. However, when competition between hubs is moderate, competition completely dominates cooperation. In other words, competition is strictly better in Z_2 and not worse in Z_1, as illustrated in **Figure 4(d)**. These dynamics were observed only when the hubs are geographically distant, not when they are located close together. For hubs located nearby, neither cooperation nor competition dominated, regardless of which hub had lower costs or whether the competition was aggressive or moderate. **Figure 4(e)** shows that neither strategy-cooperative hub ports located close together nor competitive hubs located close or far apart-dominated the other. Co-operation was effective only in reducing Z_2 but not in promoting sustainability.

Sensitive analysis of changes in the levels of cooperation/competition: 1) hub ports cooperating only on transshipment costs, and 2) both cooperative hubs located close together acting as getaways-revealed Pareto solutions similar to those found under competitive conditions above, for the first scenario, and for hub ports located both close and far apart. However, the Pareto obtained when both cooperative hubs located close together acted as getaways was inferior to the Pareto obtained when only one hub functioned as a getaway. The latter highlights that implementing cooperative hubs located close together, with only one acting as a getaway, results in better cost savings, Figure 4(f).

Further simulations were carried out to account for contemporary geopolitical uncertainty, which often entails economical events. The paper considers a case where cargo volume increases by 40%, affecting hub port handling productivity. In a second scenario, the paper considers the simultaneous occurrence of multiple economic events (i.e., cargo volume increases by 40%, while lease costs, fuel prices, and emission costs by 50%, and vessel daily charter and operational costs decrease to 100US$/day· ton$^{\alpha_2}$). The results are displayed in Figure 5 and reveal that the final outcomes remain consistent across temporal data variations. In other words, a moderate competition strategy between hub ports located far apart dominates cooperation, while no dominance is observed when hubs are located close together. These findings differ from previous discussed literature, specifically (Li & Oh, 2010) which generally emphasizes cooperation over competition. For hub ports located closer together, it is not possible to implement either strategy without negatively impacting at least one objective in liner shipping, e.g., sustainability and/or delivery reliability. However, for hubs located farther apart, moderate competition proves to be a strictly better strategy than cooperation.

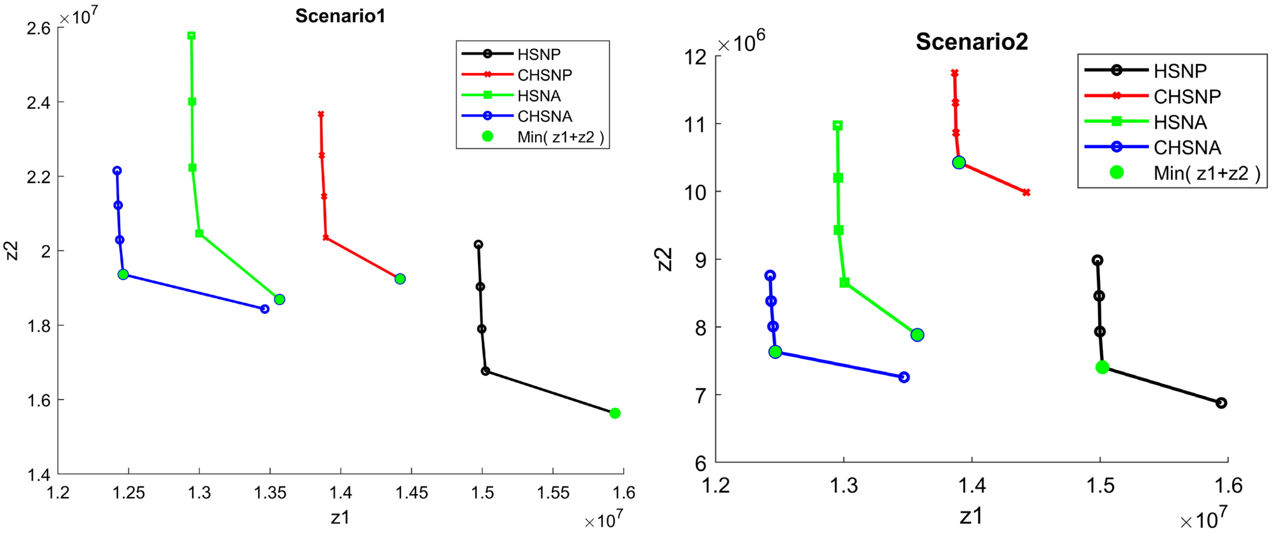

Figure 5. Set of non-dominated and dominated solutions from the sensitivity analysis

6. Conclusion

Providing reliable logistics service is crucial to enhance the overall competitive advantage of liner shipping and potentially crowd out competitors. Consequently, many liners shipping started integrating (vertically and horizontally) to increase their size and take control of the entire supply chain activities. However, the fundamental characteristic of liner shipping is its heavy reliance on port infrastructures and the managerial decisions of port authorities.

This paper examines how cooperation vs. competition between hub ports impacts the design of a cost-effective and reliable logistical network for containerized liner shipping. Since cost-effective, reliable logistics services are normally inversely proportional to unreliable service, liner shipping faces a cost tradeoff. This paper reflects the latter via a bi-objective mixed integer nonlinear optimization model. Numerical experiments were conducted for the West Africa-Europe-South America transatlantic supply chain. The main focus was placed on the West African region due to its geographical characteristics (extensive coastlines and located at the Atlantic shipping crossroads). Ports in this region offer equal spatial competitive advantages to assume regional hub status, which triggers competition vs. cooperation.

In addition, this paper addresses a gap in the literature, which often combines conflicting objectives in liner shipping into a single objective. Contrary with much of the prior empirical literature that emphasizes port cooperation over competition, the findings in this paper reveal that moderate competition is strictly better than cooperation for geographically distant hub ports. However, for hubs located closer together, neither cooperation nor competition can be implemented without negatively affecting at least one objective in liner shipping, such as delivery reliability and/or sustainability (e.g., emissions reduction and fuel efficiency).

Given West Africa's strategic location at the Atlantic crossroads connecting Africa, Europe, and the Americas, this paper provides valuable insight for decision-making regarding hub port cooperation or competition, helping shipping companies navigate the tradeoffs between costs, reliability and sustainability.

The framework of the proposed model is that of a central planner overseeing an integrated (vertically and horizontally) liner shipping company and port operator. The central planner assumption simplifies the analysis, allowing for a focused examination of the crucial tradeoff between reliability and unreliability costs. In reality, however, port authorities may decentralize their operations through leasing contracts, and individual liners decisions are often influenced by market dynamics. Further research could investigate whether the solutions derived from the central planner model are stable under decentralized market conditions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix A

Table A1. Import and export of container trade volume in 2020 (TEU).

Ports	EXPORT (TEU)		IMPORT (TEU)	
	Europe	South America	Europe	South America
Port of Abidjan	390,668	7403	78,668	6951
Port of Conakry	2933		24,913	1463
Port of Freetown	5732		6905	6373
Port of Monrovia	3703		7008	2426
Port of Cotonou	1374		18,022	952
Port of Nouakchott	23,163	162	24,760	1224
Bissau Port	200	135	4716	178
Port of Lomé	3779		21,279	668
Port of Lagos	50,455	150	136,006	9127
Port of Tema	175,368	6890	132,540	12,705
Port of Banjul	721	1093	7796	4639
Port of Dakar	18,214	351	74,531	12,188
Port of Praia	4936		18,211	1553

Table A2. Regression equation for each port for vessel mooring, pilotage and towage[1].

Ports	$slope_i$	$Intercept_i$	R^2
Port of Abidjan	4.0967	5002.044	0.9996
Port of Conakry	0.3753	6141.4	0.9919
Port of Freetown	0.3753	6141.4	0.9919
Port of Monrovia	0.3753	6141.4	0.9919
Port of Cotonou	0.2107	686.45	0.9987
Port of Nouakchott	4.0967	5002.044	0.9996
Bissau port	4.0967	5002.044	0.9996
Port of Lomé	0.2107	686.45	0.9987
Port of Lagos	4.0967	5002.044	0.9996
Port of Tema	0.2199	5916.5	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	766.69	0.9985

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[1] In some countries, the absence of port dues cost (mooring, pilotage, and towage) was covered with costs following their closest strategic ports for simplifications. Moreover, for ports such as Abidjan, and Dakar, the cost was adapted from (Kim, Lam, & Lee, 2018), henceforth following their closest strategic ports.

Table A3. 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

Table A4. Estimations of the vessel main dimensions.

n_k	$Cap_k\,(TEU)$	v_{rik}^{speed}	Gt_k	LOA	a_k	g_k
1	154	11.6	2839	84	432.5	2.80×10^{-2}
2	365	14.5	3071	110	432.5	2.80×10^{-2}
3	442	12	5015	101	432.5	2.80×10^{-2}
4	537	13	6006	128	432.5	2.80×10^{-2}
5	804	19	7852	140	432.5	2.80×10^{-2}
6	1732	20.14	18,480	172	794	2.05×10^{-2}
7	2556	20	26,833	216	1132.2	1.69×10^{-2}
8	3868	20	42,564	223	1132.2	1.69×10^{-2}
9	4432	22	44,234	162	1132.2	1.69×10^{-2}
10	14,000	22	90,118	306	1482.2	1.45×10^{-2}