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Brazilian maritime containerized cabotage competitiveness assessment based on a multimodal super network

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ABSTRACT

This study evaluates the competitiveness of Brazilian maritime container cabotage within a multimodal transportation super network, employing an adapted All Pairs Shortest Path (APSP) algorithm to solve the All Pairs Minimum Cost Path problem. The research analyzes cost structures, environmental impacts, and operational efficiencies across 637 cities, 18 container terminals, 8 barge terminals, and 301 maritime routes. Key metrics, including freight rates, in-transit inventory costs, and CO_2 equivalent emissions, are incorporated into the network's impedance values, enabling a comprehensive comparison between maritime cabotage and road transportations modes. Results indicate that maritime cabotage holds a significant cost advantage over road transportation mode for long-haul routes, particularly when distances exceed 1.800 km. Additionally, maritime cabotage offers substantial environmental benefits, with CO_2 equivalent emission reductions of up to 41,3 %, depending on the route and cabotage shipping company.

1. Introduction

Brazil, the largest country in South America, spans approximately 8.5 million square kilometers and features diverse geographical characteristics, including vast rainforests, extensive river systems, and a long Atlantic coastline (IBGE, 2024). Despite these natural advantages, Brazil's transportation system is heavily reliant on road transportation mode, which accounts for 64 % of the modal share (PNL, 2024). This overreliance on road transportation results in significant inefficiencies, such as excessive costs, environmental degradation, and congestion (Júnior et al., 2022). In contrast, maritime cabotage transportation mode, a potentially sustainable alternative, represents just under 11 % of total cargo transport (ABAC, 2024).

Efforts to promote maritime cabotage, such as the BR do Mar Program (Law 14.301/2022), aim to address infrastructural and regulatory barriers, fostering a more balanced transportation matrix and mitigating negative road transportation impacts, including accidents and pollution (Rohm, 2022; Barbosa et al., 2022). However, despite these legislative measures, the full potential of maritime cabotage transportation mode remains underutilized, particularly regarding its competitiveness with road transportation mode (Santana et al., 2021).

While the literature emphasizes the strategic importance and operational challenges of Brazilian maritime cabotage, there is a notable gap in understanding its competitive positioning relative to road transportation mode across various city pairs. Specifically, comprehensive research comparing total logistics costs and CO_2 equivalent (CO_2eq) emissions between maritime cabotage and road transportation mode for different origin-destination combinations is lacking. Furthermore, the relationship between maritime cabotage's competitiveness and the aggregate distance traveled—including road segments to and from ports—compared to direct road transportation distances has been insufficiently explored. This gap is crucial as it limits shippers' ability to make informed decisions about incorporating maritime cabotage into their supply chains. Additionally, it hinders maritime cabotage companies from effectively tailoring services and marketing strategies to enhance competitiveness in specific geographic areas. Addressing this research gap would provide valuable insights for optimizing multimodal transportation choices and potentially identify distance thresholds at which maritime cabotage becomes more advantageous than road transportation mode, contributing to the advancement of efficient and sustainable logistics practices in Brazil.

This study seeks to answer two primary research questions within the context of Brazilian multimodal transportation. First: "For which city pairs in Brazil does maritime cabotage transportation mode demonstrate

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superior competitiveness compared to road transportation mode, considering freight rates, in-transit inventory costs, and CO_2eq emissions costs?" Second: "What is the relationship between the competitiveness of maritime cabotage and the aggregate pre- and on-carriage distances compared to the direct road transportation mode distance between origin and destination cities?" These questions guide a comprehensive evaluation of maritime cabotage competitiveness in Brazil, using a multimodal transportation super network model, an advanced mathematical framework that integrates multiple transportation modes to evaluate the competitiveness of maritime cabotage against road transportation mode. The analysis focuses on Brazilian cities with populations exceeding 50,000, considering both economic and environmental factors.

The article is structured as follows: Section 2 provides a comprehensive literature review, while Section 3 outlines the problem description. Section 4 details the development of mathematical models. Case studies are discussed in Section 5, and Section 6 concludes with findings and recommendations for future research. For the purposes of this article, container transportation via maritime cabotage is referred to as "cabotage transportation mode" or simply "cabotage."

2. Literature review

In addition to the literature on Brazilian cabotage transportation, a thorough assessment of its competitiveness compared to road transportation mode requires incorporating key domains such as Short Sea Shipping (SSS), Modal Shift, and Multimodal Network analysis. Each of these domains offers critical insights that are essential for understanding and evaluating maritime cabotage transportation within Brazil's logistics framework.

2.1. Brazilian maritime cabotage

The existing literature on Brazilian maritime cabotage, though limited, addresses several key themes, including its strategic importance, policy development, environmental integration, operational challenges, market analysis, and feasibility studies. Maritime cabotage plays a strategic role in Brazil's transportation system, contributing to economic growth, sustainability, and national sovereignty. Soares (2022) provides a comprehensive analysis of cabotage's significance in the national transport system and emphasizes the need for targeted public policies to address inefficiencies. De Valois et al. (2012) explore the potential of Short Sea Shipping (SSS) in Brazil, suggesting that a shift towards SSS could help mitigate logistical challenges, reduce costs, and provide environmental benefits. Paixão Casaca et al. (2017) highlight market challenges such as inadequate port infrastructure and high operational costs, while emphasizing the potential for greater multimodality and integration with other transport modes.

Casaca and Lyridis (2018) discuss the global complexity of cabotage policies, noting the delicate balance between protectionist and liberalized approaches. da Silva et al. (2022) underscore cabotage's efficiency in transporting large volumes over long distances due to its higher capacity and lower operational costs. However, challenges such as high fuel prices, bureaucratic hurdles, and insufficient port infrastructure hinder its growth. The authors recommend aligning fuel prices with international standards and reducing bureaucratic obstacles to promote sector expansion. Operational challenges are further examined by Júnior et al. (2022), who assess user satisfaction in the containerized cargo segment, identifying areas for improvement, such as reducing transportation costs and enhancing service quality. Additionally, Júnior et al. (2021) present a critical analysis of cabotage's operational challenges in Brazil, employing a Multicriteria Decision Aid (MCDA) methodology to evaluate deficiencies in the sector.

Hjelle (2011) critically examines the competitive dynamics between short sea shipping and road transportation, focusing on the Ro-Ro (Roll-on/Roll-off) shipping model. The study highlights the environmental advantages of maritime transport but also points to complexities such as energy inefficiencies and the 'double load factor problem,' which can reduce the perceived environmental benefits of SSS. Yamahaki et al. (2024) examine the integration of climate change considerations into Brazil's cabotage policies, noting that while cabotage offers environmental benefits, climate concerns were neglected in the legislative process of the "BR do Mar" policy.

While the strategic importance and challenges of Brazilian cabotage are well-documented, understanding its competitiveness in specific transport scenarios requires a deeper exploration of short sea shipping and modal shift, which is discussed in the following section.

2.2. Short Sea shipping (SSS) and modal shift

The selection of freight transport modes is a critical aspect of modern logistics, requiring a detailed assessment of factors such as efficiency, cost-effectiveness, environmental impact, and sustainability. Cui et al. (2015) and Gao (2019) highlight the growing preference for sustainable transport modes, including intermodal rail and Short Sea Shipping (SSS), to mitigate the challenges of unimodal road transport, particularly congestion and environmental degradation. Morales-Fusco et al. (2012) evaluate the competitiveness of Motorways of the Sea (MoS) for freight distribution, emphasizing that unaccompanied sea transport can achieve cost-effectiveness through economies of scale, though it requires significant investment and coordination.

Meers and Macharis (2015) introduce a GIS-based macro-scan methodology to identify promising freight flows for modal shift in the Flanders region, demonstrating its potential to prioritize transport flows for a transition from road to sea. Lupi et al. (2017) compare the competitiveness of MoS with road transport between mainland Italy and Sicily, finding that while intermodal transport is more cost-effective, MoS often results in longer transit times. Konstantinus et al. (2019) provide a comprehensive analysis of the barriers and enablers for SSS in the Southern African Development Community (SADC), emphasizing the role of SSS in enhancing regional freight transport and intermodal connectivity, which is crucial for fostering economic growth and trade efficiency in the context of maritime cabotage.

Chandra et al. (2016) explore the shift from road-based to coastal shipping for automotive logistics in India, highlighting significant cost and environmental benefits, though they emphasize the need for investments in port infrastructure to support this shift.

Comi and Polimeni (2020) provide a comprehensive analysis of SSS in the Mediterranean, demonstrating how SSS alleviates road congestion and reduces external costs. Raza et al. (2020) identify gaps in the research on transitioning from road transport to SSS, noting inconsistent results across studies due to varied methodologies and calling for more route-specific, realistic analyses. Pérez-Mesa et al. (2020) find that intermodal transport, combining road and SSS for vegetable exports from Southeast Spain to the United Kingdom, can reduce both costs and environmental impact.

Recent studies, such as those by Raza et al. (2020) and Ramalho and Santos (2021), emphasize the strategic shift from road transport to SSS as a viable solution to environmental and economic challenges, advocating for the internalization of external costs and the implementation of supportive policies. Hoff et al. (2010) provide a comprehensive overview of fleet composition and routing in both maritime and road transportation, elucidating the operational challenges involved in optimizing transportation modes, while Fancello et al. (2019) focus on optimizing network design for Ro-Ro freight transport in the Tyrrhenian area, showing how integrated services can enhance efficiency compared to road transport.

To fully understand the competitiveness of Brazilian cabotage, it is essential to examine how multimodal networks can optimize transportation costs, which leads to the next area of review.

2.3. Multimodal network

Chang et al. (2010) developed an optimization model for container transportation in South Korea, highlighting Short Sea Shipping (SSS) as an environmentally friendly alternative to road transport. The model aims to minimize logistics costs, including shipping, land transport, and externalities such as air pollution and greenhouse gas emissions. A case study demonstrates the benefits of redirecting freight traffic to SSS and rail, supporting policies that advocate for sustainable transportation. Similarly, Wong et al. (2010) proposed a multimodal network design model for container transport in Taiwan, integrating SSS and trucking to mitigate environmental and congestion costs. Their model evaluates government policies that incentivize SSS by internalizing external costs and investing in infrastructure, aiming to reduce transportation costs while accounting for societal and environmental impacts.

Zhao et al. (2019) presented an optimization model for export container transport along the Yangtze River Economic Belt, focusing on river-sea and combined shipping. Using a genetic algorithm, the model minimizes transportation costs and externalities, identifying optimal locations for dry ports and hub river ports. This study demonstrates the model's effectiveness in optimizing multimodal transportation, reducing costs, and lowering environmental impacts, underscoring the potential of river-sea shipping.

Yang et al. (2021) introduced a model to enhance the sustainability of coastal container multimodal transportation systems by optimizing network design and toll policies to reduce carbon dioxide emissions. Based on empirical data from the Bohai Rim in Northeast China, the model achieves a 3.29 % to 6.70 % reduction in emissions, showing that strategic investments and policy adjustments can significantly lower emissions while maintaining economic feasibility.

Ilie and Mitran (2014) provide a critical analysis of intermodal dynamics between maritime and road transportation, particularly within the context of the Constanta Port. By evaluating trip generation and attraction potentials, the authors elucidate how these factors can inform the optimization of logistics facilities, thereby highlighting the competitive interplay between short sea shipping and road transport modes in enhancing overall transport efficiency. Hemmidy et al. (2018) focused on optimizing container flow within a multimodal network, proposing a mathematical model that minimizes transportation costs by considering port and vehicle capacities, as well as storage and handling costs. This model incorporates road, rail, and river transport to enhance operational efficiency, providing a robust framework for decision-making in multimodal logistics.

2.4. Literature review conclusion

Although the existing literature highlights the strategic importance of maritime cabotage, the potential of SSS, and the advantages of multimodal network optimization, a comprehensive analysis of cabotage's competitiveness in Brazil remains underexplored. Notably, there is a lack of research that integrates logistics costs, in-transit inventory costs, and CO_2eq emissions and costs into a unified framework for assessing maritime cabotage within a multimodal network. This study aims to fill this gap by providing a detailed evaluation of Brazilian maritime cabotage's cost competitiveness in comparison to road transportation mode, incorporating environmental and economic factors to offer a more complete picture of its role in sustainable logistics in Brazil.

3. Problem description

This study examines the computation of minimum cost paths for both cabotage and road transportation modes across 673 Brazilian cities, each with populations exceeding 50,000, within a comprehensive multimodal transportation super network. The goal is to assess the competitiveness of cabotage transportation mode in comparison to road transportation mode. The super network comprises 637 cities, 18 container terminals, 8 barge terminals, and 17 empty container depots, resulting in 680 georeferenced nodes.

Certain Brazilian cities are accessible only through a combination of road and waterway transportation, while cabotage necessarily involves pre- and on-carriage via road transportation, and, in some cases, a combination of waterway and road transportation modes. Therefore, the comparison between road and cabotage transportation modes can be understood as a comparison between two multimodal systems. Multimodal transport refers to the use of different modes, such as road, rail, air, and maritime, integrated into a single journey or logistical operation. This approach offers advantages such as greater efficiency, cost reduction, and lower environmental impact. The integration of multiple transport modes within a single operation, managed by one operator, facilitates door-to-door services (Udo et al., 2019).

The problem addressed in this research is an instance of the All Pairs Shortest Paths (APSP) problem, which involves identifying the shortest paths between all pairs of nodes within a network. This is a critical task for optimizing logistics and transportation systems, as emphasized by Archetti et al. (2022). In this context, the costs associated with both road and cabotage transport modes are incorporated into the impedance values of the network links, replacing the traditional distance metric used in the shortest path problem. Consequently, the problem is framed as an All Pairs Minimum Cost Path problem, with cost components including basic freight charges, in-transit inventory costs, and CO_2eq emissions costs.

One illustrative example is presented to facilitate the development and understanding of the multimodal super network models, serving as a critical tool for elucidating the complexities inherent in the networks and demonstrating the factors influencing the computation of minimum cost paths. The example examines transportation routes from Campinas, one of the largest cities in the interior of São Paulo, to Macapá, the capital of Amapá, as depicted in Fig. 1. Notably, the state of Amapá is inaccessible by road. Therefore, both road and cabotage transportation modes require an on-carriage leg via inland waterway to complete their journeys.

All cabotage companies call at Manaus Port, which has inland waterway connections to Amapá. Consequently, containers are discharged at the Port of Manaus, followed by an on-carriage leg by inland waterway from Manaus to the barge terminal in Santana, Amapá. Similarly, road transportation necessitates an on-carriage leg via the Barge Terminal in Vila do Conde, Pará, to reach Macapá. These multi-leg routes for both transportation modes result in additional in-transit inventory and CO_2eq emissions costs, which are added to the basic freight charges. It is important to note that container shipment in cabotage involves two additional road transport legs. The first leg involves picking up an empty container from a container depot and transporting it to the city where the shipper is located for cargo stuffing. The second leg involves returning the empty container to a depot near the destination city after it has been stripped at the consignee's premises.

In this example, the routes for each transportation mode are outlined as follows:

- Road: Campinas, SP - > Barge Terminal at Vila do Conde, PA - > Barge Terminal at Santana, AP - > Macapá, AP.
- Cabotage: Depot at Santos, SP - > Campinas, SP - > Container Terminal at Santos Port, SP - > Container Terminal at Manaus Port, AM - > Barge Terminal at Manaus, AM - > Barge Terminal at Santana, AP - > Macapá, AP - > Depot at Santana, AP.

This study addresses a path choice problem within the mathematical framework of a multimodal transportation system, incorporating inland waterways, highways, and cabotage routes. In such systems, the concept of super networks provides a comprehensive model for integrating diverse transportation modes - such as road, cabotage, and inland waterways -into a unified system. Super networks, described as "networks of networks," allow for the modeling of complex interdependencies and

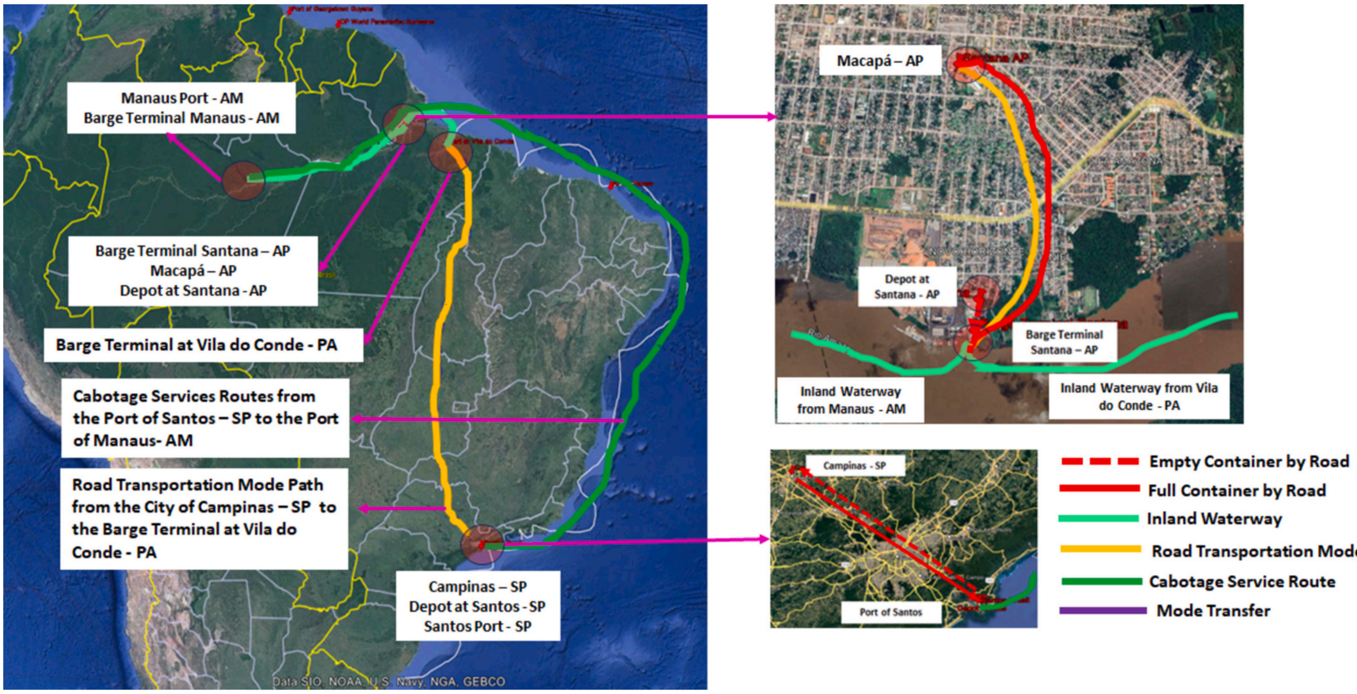

Fig. 1. Example Map (Source: Authors).

constraints across different transportation modes, thereby improving the efficiency and sustainability of logistics operations (Nagurney and Wakolbinger, 2005).

This approach is particularly relevant for multimodal networks, where the integration of distinct transportation modes can optimize cargo flows, reduce fuel consumption, and minimize carbon emissions. By capitalizing on the strengths of each mode, super networks facilitate more effective planning and management, contributing to the development of sustainable and cost-efficient transportation solutions (Liao et al., 2014).

Fig. 2 presents an abstract representation of the super network, where the links correspond to physical routes—such as highways, inland waterways, and cabotage routes—and transitions between transportation modes. This conceptual model illustrates the interconnected nature of the multimodal transportation system, demonstrating how the integration of various modes is achieved within a unified network

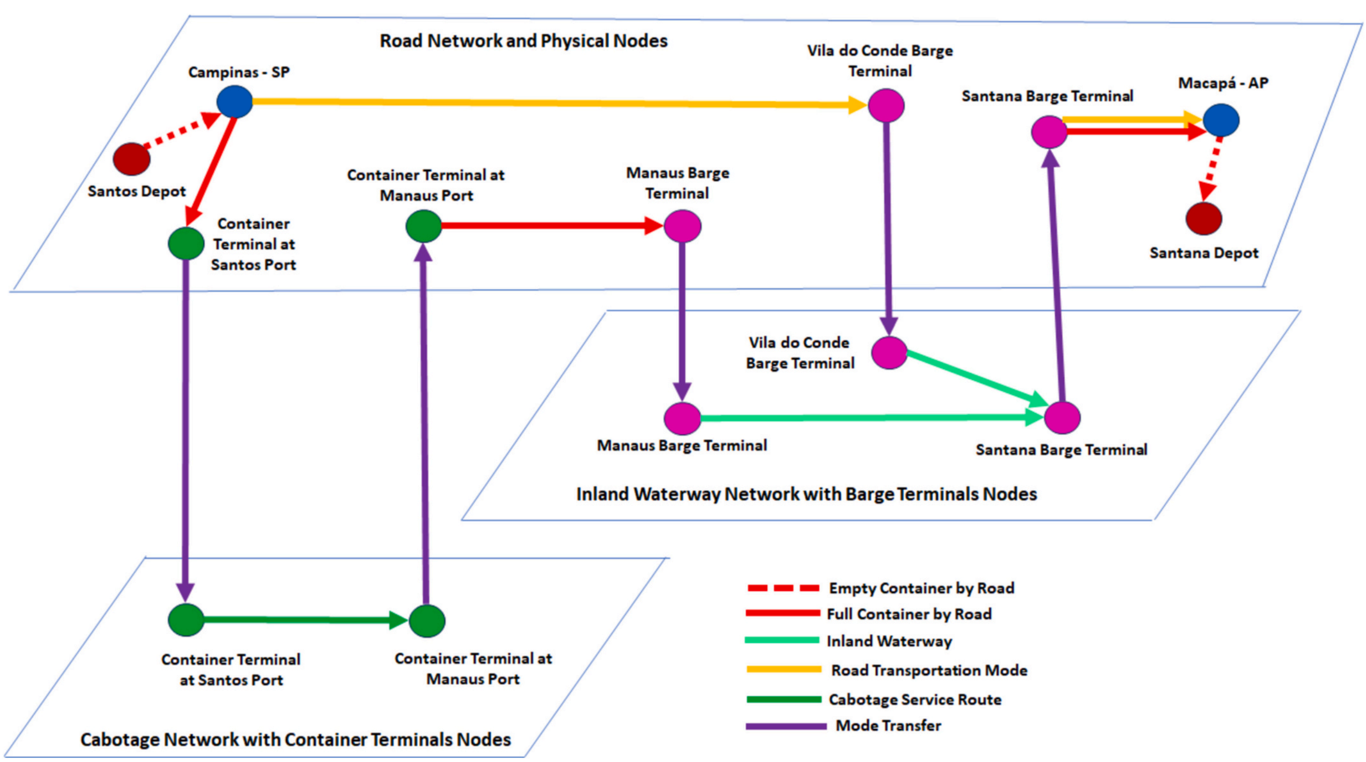

Fig. 2. Super Network for the Example (Source: Authors).

framework.

Considering this example and the study's aim to compare road and cabotage transportation modes, each mode operates within its own super network: S_R for the road transportation mode and S_C for cabotage transportation mode. These super networks represent the distinct infrastructure and operational dynamics of each mode, enabling a detailed comparison of their performance.

Considering the topology of the super networks, the following node sets are introduced:

- N_{DP}: set of Container Depot (DP) nodes
- N_{CY}: set of City (CY) nodes.
- N_{BT}: set of Barge Terminal (BT) nodes.
- N_{CT}: set of Container Terminal (CT) nodes.

The corresponding arcs, representing the links between the nodes, are defined as follows:

- A_{DP-CY}: set of arcs between Container Depots (DP) and Cities (CY).
- A_{CY-DP}: set of arcs between Cities (CY) and Container Depots (DP).
- A_{CY-CY}: set of arcs between Cities (CY).
- A_{CY-BT}: set of arcs between Cities (CY) and Barge Terminals (BT).
- A_{BT-CY}: set of arcs between Cities Barge Terminals (BT) and Cities (CY).
- A_{CY-CT}: set of arcs between Cities (CY) and Container Terminals (CT).
- A_{CT-CY}: set of arcs between Container Terminals (CT) and Cities (CY).
- A_{BT-CT}: set of arcs between Barge Terminals (BT) and Container Terminals (CT).
- A_{CT-BT}: set of arcs between Container Terminals (CT) and Barge Terminals (BT).
- A_{BT-BT}: set of arcs between Barge Terminals (BT).
- A_{CT-CT}: set of arcs between Container Terminals (CT).

The super network for road transportation mode, S_R, is defined as $S_R = (N_R, A_R)$, (where)

- $N_R = N_{CY} \cup N_{BT}$ is the union of all cities and barge terminals nodes.
- $A_R = A_{CY-CY} \cup A_{CY-BT} \cup A_{BT-CY} \cup A_{BT-BT}$ is the union of all road's arcs connecting the cities, cities and barge terminals and the inland waterway routes.

The super network for cabotage transportation mode, S_C, is defined as $S_C = (N_C, A_C)$, (where)

- $N_C = N_{CY} \cup N_{BT} \cup N_{CT} \cup N_{DP}$ is the union of all cities, barge terminals, container terminals and container depots nodes.
- $A_C = A_{DP-CY} \cup A_{CY-DP} \cup A_{CY-BT} \cup A_{BT-CY} \cup A_{CY-CT} \cup A_{CT-CY} \cup A_{BT-CT} \cup A_{CT-BT} \cup A_{BT-BT} \cup A_{CT-CT}$ is the union of all arcs connecting the cities to container depots, cities to barge terminals, cities to container terminals, barge terminals to container terminals, and inland waterway routes and cabotage routes.

4. Mathematical models

This section outlines the methodology used to assess the total transportation costs for both cabotage and road transportation modes. The analysis involves calculating base freight charges, in-transit inventory costs, and CO_2eq emissions costs for each mode. By integrating these cost components into a unified framework, the model identifies the most cost-effective transportation option over various distances.

Although recent studies on modal shift advocate for the internalization of external costs (Raza et al., 2020; Ramalho and Santos, 2021), publicly available data in Brazil remains limited, preventing a comprehensive analysis of externalities in freight transport mode choice. As a result, this study calculates the costs for each transportation mode by incorporating freight charges, in-transit inventory costs, and CO_2eq emissions costs.

The 'in-transit inventory cost' refers to the cost of holding goods while they are being shipped. It includes expenses related to the capital tied up in inventory during the transportation period.

Emissions are calculated using the Fuel-based method, which determines the amount of fuel consumed and applies the corresponding emission factor for that fuel. This approach provides a comprehensive assessment of the environmental impact for each transportation mode (GHP, 2020).

4.1. Road transportation model

This study does not reference previous research on the cost structure and freight rates for road transportation in Brazil. Instead, it employs the methodology and values from Resolution No. 5.867 of January 14, 2020, issued by the Brazilian National Land Transport Agency (ANTT 1, 2024) to calculate minimum freight rates for road transport. This resolution defines the general rules, methodology, and coefficients for determining the minimum freight rates per kilometer traveled in the provision of remunerated road freight transport services, calculated per loaded axle, as established by the National Minimum Freight Policy for Road Freight Transport (PNPM-TRC). For Full Truckload (FTL) operations, the minimum freight rate is computed by multiplying the distance traveled between origin and destination by the displacement coefficient (CCD) and adding the loading and unloading coefficient (CC).

The PNPM-TRC parameters used in this research are based on Resolution No. 6.034 of January 18, 2024 (ANTT 2, 2024), which updates the CCD and CC values for a 6-axle truck tractor-trailer combination, as outlined in Resolution No. 5.867. Since the PNPM-TRC does not include a profit margin in its freight calculations, this study incorporates an EBIT margin of 15.0 % for a transport company (JSL, 2024) over the cost to estimate the freight rate for the road transportation mode. The mathematical model considers the following:

4.1.1. Sets and Indices

- Let i represents the origin node.
- Let j represents the destination node.
- Let N_R be the set of all nodes for road transportation mode, $(i,j) \in N_R$.

4.1.2. Parameters

- M_R: Road Transportation Mode EBIT margin, in %.
- $D_{i,j}$: Distance between origin node i and destination node j, in kilometers.
- Tcd : PNPM-TRC cost parameter for a 6-axle truck tractor-trailer combination, in BRL per kilometer.
- Tcc : PNPM-TRC load and discharge cost parameter for a 6-axle truck tractor-trailer combination, in BRL.
- d : Maximum distance a truck can cover per day, in kilometers.
- v : Cargo value, in BRL.
- i : Capital cost rate, in % per day.
- F_c^D : Diesel fuel consumption for a 6-axle truck tractor-trailer combination, in liters/km.
- F_e^D : Diesel fuel energy content, in MJ/l.
- F_f^D : Diesel fuel WTW emission factor, in gCO_2eq/MJ.
- Cp : Carbon price, in BRL/tCO_2eq.

4.1.3. Cost function

$C_{i,j}^R$: Road transportation mode cost between origin node i and destination node j, $\forall (i,j) \in N_R$, in BRL.

The cost for the road transportation mode between origin node i and destination node j is calculated using the following equation:

$$C_{i,j}^{R} = \frac{1}{(1-M_R)}\left(\mathrm{D}_{i,j}Tcd + Tcc\right) + \frac{D_{i,j}}{d}vi + D_{i,j}F_c^D F_e^D \frac{F_f^D}{1000000}Cp \tag{1}$$

Eq. (1) incorporates the base freight cost, in-transit inventory cost, and CO_2eq emission cost for the road transportation mode cost function.

4.2. Inland waterway transportation model

The cost calculation for inland waterway transportation mode, whether for a 6-axle truck tractor-trailer combination or a 40′ container, is based on publicly available tariffs from a waterway transport company operating in the Amazon region (Grupo Chibatão, 2024). Using these tariffs as a reference, a set of parameters has been formulated to calculate costs associated with inland waterway transportation, considering marine diesel oil (MDO) as the standard fuel for barges.

4.2.1. Sets and indices

- Let i represents the origin barge terminal.
- Let j represents the destination barge terminal.
- Let N_{BT} be the set of all nodes for inland waterway transportation mode, $(i,j) \in N_{BT}$.

4.2.2. Parameters

- $D_{i,j}$: Distance between an origin barge terminal i and a destination barge terminal j, in kilometers.
- S^u : Barge speed when navigating upstream the river, in in kilometers per hour.
- S^d : Barge speed when navigating downstream the river, in kilometers per hour.
- Dc : Daily cost for a 6-axle truck tractor-trailer combination or for a 40′ container while on the barge, in BRL per day.
- v : Cargo value, in BRL.
- i : Capital cost rate, in % per day.
- F_c^M : Barge's MDO fuel consumption per 6-axle truck tractor-trailer combination or per 40′ container while on the barge, in tons per day.
- F_e^M : MDO fuel energy content, in MJ/l.
- F_f^M : MDO fuel WTW emission factor, in gCO_2eq/MJ.
- Cp : Carbon price, in BRL/tCO_2eq.
- h: Handling cost at both barge terminals for a 6-axle truck tractor-trailer combination or for a 40′ container, in BRL.

4.2.3. Cost Functions.

For the waterway transportation mode between origin barge terminal i and destination barge terminal j, the cost is calculated using different equations for upstream and downstream segments, $i,j \in A_W$, in BRL.

- Upstream Segment ($C_{i,j}^{WU}$)

$$C_{i,j}^{WU} = \frac{D_{i,j}}{S^u}\left(Dc + vi + F_c^M F_e^M \frac{F_f^M}{1000000}Cp\right) + h \tag{2}$$

- Downstream Segment ($C_{i,j}^{WD}$)

$$C_{i,j}^{WD} = \frac{D_{i,j}}{S^d}*\left(Dc + vi + F_c^M F_e^M \frac{F_f^M}{1000000}Cp\right) + h \tag{3}$$

Eqs. (2) and (3) account for the base freight cost, in-transit inventory cost, CO_2eq emissions cost, and handling costs for upstream and downstream river segments, respectively.

4.3. Cabotage transportation model

The cost calculation for the cabotage transportation mode is based on proformas developed for services provided by four major cabotage shipping companies operating in the container segment: Aliança, Log-In, Mercosul Line, and Norcoast. A proforma is a comprehensive document outlining the terms and conditions of a standard container service offered by a shipping company, covering aspects such as service schedules, ports of call, vessel capacity, service frequency, and other operational details (Ducruet and Notteboom, 2012).

In this study, proformas are constructed using service schedules published online by the cabotage shipping companies. These schedules reveal that all routes follow a circular pattern, where the journey begins and ends at the same port, forming a complete loop. The proformas enable the calculation of the base cost for each cabotage service by accounting for the direct costs associated with the service. These costs include:

- Daily operational costs of the vessel, which encompass capital or charter costs, insurance, maintenance, and crew expenses.
- Fuel consumption costs, specifically for Marine Diesel Oil (MDO) and Very Low Sulfur Fuel Oil (VLSFO).
- Port call costs, which include expenses for pilotage, tugboats, and port fees.

MDO consumptions at port and at sea were obtained from a Brazilian Cabotage company and VLSFO consumption calculation is based on the work of Yao et al. (2012) that explored the correlation between bunker fuel consumption rate (F) and ship speed (V) across various container ship sizes. They established an empirical model, $F = k_1V^3 + k_2$ to represent this relationship. In their model, 'F' represents the bunker fuel consumption rate in tons/day, 'V' indicates the ship speed in knots, and 'k_1' and 'k_2' are coefficients. Based on their work and considering the average cabotage fleet size in TEU, this study adopts the values of $k_1 = 0{,}006754$ and $k_2 = 37{,}23$.

Once the service cost is determined, the cost per Twenty-Foot Equivalent Unit (TEU), known as the slot cost, is calculated by dividing the total service cost by the average operational capacity, in TEUs, deployed in the service. This study assumes that the ship's operational capacity is 80 % of its nominal TEU capacity. The slot cost is a key parameter for pricing the cabotage service, representing the minimum price per TEU required to cover the service's operational costs (Parthibaraj et al., 2018; Pasha et al., 2020).

Additionally, the study calculates transit times between ports and the CO_2eq emissions for each service. Emissions are estimated by dividing the total emissions from maritime fuel consumption (VLSFO and MDO) by the total travel time and the vessels' average operational capacity, expressed in TEUs. This calculation results in an emissions parameter represented as tCO_2eq per day per TEU.

4.3.1. Sets and Indices

- $S = \{1, 2, \dots, s\}$ represents the cabotage companies' services.
- $P_s = \{1, 2, .., n-1, n\}$ represents the container terminals in the service s, where $n-1$ is the number of container terminals and n represents the return to the first container terminal to complete the service schedule's route as a closed circuit, $P_s \in N_C$.

4.3.2. Parameters

- $ETA_{s,i}$: Estimated Date and Time of Arrival port i, for $i \in P_s$, for service $s \in S$.
- $ETB_{s,i}$: Estimated Date and Time of Berthing at port i, for $i \in P_s$, for service $s \in S$.
- $ETS_{s,i}$: Estimated Date and Time of Sailing from port i, for $i \in P_s$, for service $s \in S$.

- $D_{i,i+1}$: Distance between ports i and $i+1$, for $i \in P_s$, in nautical miles.
- $S^{PC}_{s,i}$: Ship port call costs at port i, for $\forall i \in P_s$, for service $s \in S$, in BRL.
- S^{DC}_{s}: Ship daily cost, for service $s \in S$, in USD per day,
- S^{TEU}_{s}: Ship average capacity, for service $s \in S$, in TEU.
- F^{MC}: MDO fuel cost, in USD per ton.
- F^{MRP}: MDO fuel consumption rate at port, in tons per day.
- F^{MRV}: MDO fuel consumption rate during sea voyage, in tons per day.
- F^{VC}: VLSFO fuel cost, in USD per ton.
- k_1: Coefficient for speed-related VLSFO consumption.
- k_2: Constant for VLSFO consumption, in ton per day.
- F^{M}_{e} : MDO fuel energy content, in MJ/ton.
- F^{M}_{f} : MDO fuel WTW emission factor, in gCO_2eq/MJ.
- F^{V}_{e} : VLSFO fuel energy content, in MJ/ton.
- F^{V}_{f} : VLSFO fuel WTW emission factor, in gCO_2eq/MJ.
- ROE : Rate of Exchange BRL/USD.
- THC_i: Terminal Handling Charge at origin container terminal, $i \in P_S$, in BRL.
- THC_j: Terminal Handling Charge at destination container terminal, $j \in P_S$, in BRL.
- v : Cargo value, in BRL.
- i : Capital cost rate, in % per day.
- Cp : Carbon price, in BRL/tCO_2eq.
- M_c: Cabotage Transportation Mode EBIT margin, in %.

4.3.3. *Cost functions.*

a) Cabotage service cost SC_s.

The cabotage service cost SC_s, for service $s \in S$, in BRL, is calculated as follow:

$$SC_s = ROE\, S^{DC}_s \left(\sum_{i \in P_S, i<n} \frac{ETS_{s,i} - ETA_{s,i}}{24} + \sum_{i \in P_S, i<n} \frac{ETB_{s,i+1} - ETS_{s,i}}{24} \right) + ROE\, F^{MC} \left(\left(F^{MRV} \sum_{i \in P_S, i<n} \frac{ETS_i - ETA_i}{24} \right) + \left(F^{MRP} \sum_{i \in P_S, i<n} \frac{ETB_{i+1} - ETS_i}{24} \right) \right) + ROE\, F^{VC} \left(\sum_{i \in P_S, i<n} \left(k_1 \left(\frac{D_{i,i+1}}{ETB_{s,i+1} - ETS_{s,i}} \right)^3 + k_2 \right) \right) + ROE \sum_{i \in P_S, i<n} S^{PC}_{s,i} \tag{5}$$

Eq. (5) includes the total ship cost, MDO consumption cost, VLSFO consumption cost, and port call costs.

b) Cabotage slot cost $SLOTC_s$

The cabotage slot cost $SLOTC_s$, for service $s \in S$, in BRL per TEU, is calculated as:

$$SLOTC_s = \frac{SC_s}{S^{TEU}_s} \tag{6}$$

c) Cabotage total emissions TE_s

Cabotage total emissions TE_s, for service $s \in S$, in tCO_2eq, are calculated as:

$$TE_s = F^M_e F^M_f \left(\left(F^{MRV} \sum_{i \in P_S, i<n} \frac{ETS_i - ETB_i}{24} \right) + \left(F^{MRP} \sum_{i \in P_S, i<n} \frac{ETB_{i+1} - ETS_i}{24} \right) \right) + F^V_e F^V_f \left(\sum_{i \in P_S, i<n} \left(k_1 \left(\frac{D_{i,i+1}}{ETB_{s,i+1} - ETS_{s,i}} \right)^3 + k_2 \right) \right) \tag{7}$$

Eq. (7) accounts for the CO_2eq emissions related to both MDO and VLSFO consumption.

d) Cabotage Emission Factor EF_s

The Cabotage emission factor EF_s, for service $s \in S$, in tCO_2eq per TEU per day, is calculated as:

$$EF_s = \frac{TE_s}{S^{TEU}_s \left(\sum_{i \in P_S, i<n} \frac{ETS_{s,i} - ETB_{s,i}}{24} + \sum_{i \in P_S, i<n} \frac{ETB_{s,i+1} - ETS_{s,i}}{24} \right) 1.000.000} \tag{8}$$

Eq. (8) includes the total CO_2eq emissions divided by the ship capacity and transit time.

Finally, the cabotage base cost for a 40′ container (which occupies 2 TEUs) is calculated as the slot cost, plus the container handling costs at the origin and destination terminals (THC) and includes an EBIT margin M_c, derived from the financial results of Log-In (Log-In, 2024). The final cabotage transportation mode cost, $C^C_{S,i,j}$, from container terminal i to container terminal j for service $s \in S$, $i, j \in P_S$, in BRL, is calculated as:

$$C^C_{S,i,j} = \frac{1}{(1 - M_c)} \left(2\, SLOT_S + THC_i + THC_j \right) + \left(\sum_{i \in P_S, i<n} \frac{ETS_{s,i} - ETA_{s,i}}{24} + \sum_{i \in P_S, i<n} \frac{ETB_{s,i+1} - ETS_{s,i}}{24} \right) (vi + 2\, EF_S\, Cp) \tag{9}$$

Eq. (9) provides the comprehensive cost for cabotage transportation from container terminal i to container terminal j for a 40\` container.

4.4. *Optimization models*

In the super network model, road and cabotage transportation modes are treated as distinct systems, each with its own set of nodes and links representing cities, container depots, and terminals. Costs, including freight rates, environmental impacts, and inventory costs, are incorporated into the calculations to ensure a comprehensive comparison.

a) Road Network

The road network $S_R = (N_R, A_R)$ is represented as a directed network with cost c_{ij}, where N_R is the set of nodes and A_R is the set of directed arcs.

4.4.1. *Parameters*

- o: Origin city node, $o \in N_R$
- d: Destination city node, $d \in N_R$
- c_{ij}: Arc cost from node i to node j, $(i,j) \in A_R$

4.4.2. *Decision variable*

x_{ij}: A binary decision variable that is 1 if the path from node i to node j is included in the optimal path, and 0 otherwise.

4.4.3. *Objective function*

The objective function minimizes the total cost of the path between the origin city o and the destination city d:

$$min(o, d) = \sum_{(i,j) \in A_R} c_{ij} x_{ij} \tag{10}$$

4.4.4. *Constraints*

- Flow leaving the origin:

$$\sum_{j \in A_R} x_{o,j} = 1 \tag{11}$$

Exactly one unit of flow must leave the origin city o, ensuring that the path begins from this node.

- Flow arriving at the destination:

$$\sum_{k \in A_R} x_{k,d} = 1 \tag{12}$$

Exactly one unit of flow must arrive at the destination city d, ensuring that the path terminates at this node.

- Flow conservation:

$$\sum_{j \in A_R} x_{ij} - \sum_{k \in A_R} x_{ki} = 0 \forall i \in A_R, i \neq o, i \neq d \tag{13}$$

For any node i that is not the origin o or the destination d, the total incoming flow must equal the total outgoing flow, maintaining continuity in the path.

- Arc dependency constraint:

$$x_{ij} \leq \sum_{k:(j,k) \in A_{BT-BT}} x_{jk} \forall (i,j) \in A_{CY-BT} \tag{14}$$

If an arc from the set A_{CY-BT} (city to barge terminal) is included in the path, the next arc must be from the set A_{BT-BT} (barge terminal to barge terminal), ensuring consistency in barge terminal transitions.

- Binary decision variable:

$$x_{ij} \in \{0,1\} \forall (i,j) \in A_R \tag{15}$$

The decision variable x_{ij} must be binary, ensuring that each arc is either included or excluded from the optimal path.

b) Cabotage Network

The cabotage network $S_C = (N_C, A_C)$ is represented as a directed network with arc costs c_{ij}, where N_C is the set of nodes and A_C is the set of directed arcs.

4.4.5. Parameters

- o: origin city node, $o \in N_C$
- d: destination city node, $d \in N_C$
- c_{ij}: arc cost from node i to node j, $(i,j) \in N_C$

4.4.6. Decision variable

- x_{ij}: A binary decision variable, set to 1 if the path from node i to node j is included in the optimal path, and 0 otherwise.

4.4.7. Objective function

The objective function minimizes the total cost of the path between the origin city o and the destination city d:

$$min(o,d) = \sum_{(i,o) \in A_{DP-CY}} c_{io} x_{io} + \sum_{(i,j) \in A_C} c_{ij} x_{ij} + \sum_{(d,j) \in A_{CY-DP}} c_{dj} x_{dj} \tag{16}$$

4.4.8. Constraints

- Initial arc from container depot to city:

$$\sum_{i:(i,o) \in A_{DP-CY}} x_{io} = 1 \forall i \in N_{DP} \tag{17}$$

This constraint ensures that the first arc selected in the optimal path belongs to the set A_{DP-CY}, representing the initial connection from a container depot to a city.

- Final arc from city to container depot:

$$\sum_{j:(d,j) \in A_{CY-DP}} x_{dj} = 1 \forall j \in N_{DP} \qquad ((18)$$

The final arc in the optimal path must be of the type A_{CY-DP}, ensuring that the path ends with a connection from a city back to a container depot.

- Flow conservation:

$$\sum_{j \in N_C} x_{ij} - \sum_{k \in N_C} x_{ki} = 0 \forall i \in N_{CY} \cup N_{BT} \cup N_{CT} \tag{19}$$

This constraint guarantees flow conservation at intermediate nodes: for any node i that is not a depot, the total incoming flow must equal the total outgoing flow.

- Arc dependency for barge terminals

$$x_{ij} \leq \sum_{k:(j,k) \in A_{BT-BT}} x_{jk} \forall (i,j) \in A_{CY-BT} \cup A_{CT-BT} \tag{20}$$

If an arc from A_{CY-BT} or A_{CT-BT} (city or container terminal to barge terminal) is included in the path, the next arc must be from A_{BT-BT} (barge terminal to barge terminal), ensuring continuity in barge terminal transitions.

- Arc dependency for container terminals:

$$x_{ij} \leq \sum_{k:(j,k) \in A_{CT-CT}} x_{jk} \forall (i,j) \in A_{CY-CT} \cup A_{BT-CT} \tag{21}$$

If an arc from A_{CY-CT} or A_{BT-CT} (city or barge terminal to container terminal) is included in the path, the next arc must be from A_{CT-CT} (container terminal to container terminal), ensuring consistency in container terminal transitions.

- Binary decision variable:

$$x_{ij} \in \{0,1\} \forall (i,j) \in N_C \tag{22}$$

The decision variable x_{ij} must be binary, ensuring that each arc is either included or excluded from the optimal path.

5. Case study

This study explores the integration of Brazilian urban centers, container terminals, barge facilities, and highways to construct a super network aimed at identifying the minimum cost paths for both road and cabotage transportation modes. The primary objective is to conduct a comparative analysis of transportation costs between these two modes, determining the routes where cabotage shows a competitive advantage over road transport.

The study considers the equivalence between general dry cargo transported by road using a three-axle truck with a road trailer totaling six axles and a load capacity of 28 tons, and cabotage transportation using a 40' High Cube container, also with a capacity of 28 tons. For road, cabotage and inland waterway transportation modes, a cargo value of BRL 200.000 and a capital cost of 0,05 % per day are assumed for calculating in-transit inventory costs. Additionally, the cost of CO_2eq emissions is based on a value of BRL 356,2 per ton of CO_2eq (Reuters, 2024).

The analysis offers valuable insights into the effective incorporation of cabotage into supply chain networks, enhancing its strategic role within Brazilian logistics. Fig. 3 presents the Brazilian multimodal map, highlighting the ports relevant to this study, while Fig. 4 illustrates the Brazilian regions, states, and the number of cities per state.

5.1. Data collection

The research methodology involved a comprehensive data collection process to ensure the accuracy and reliability of the super network models and the validity of the cost comparisons and competitiveness analyses.

a) Nodes Data

Nodes within the network were established using data from the Brazilian Institute of Geography and Statistics (IBGE, 2024), focusing on cities with populations exceeding 50,000 that are accessible by road. Information on ports and container terminals was sourced from the published schedules of cabotage companies (Aliança, 2024; Log-In 1, 2024; Mercosul Line, 2024; Norcoast, 2024), while data on barge

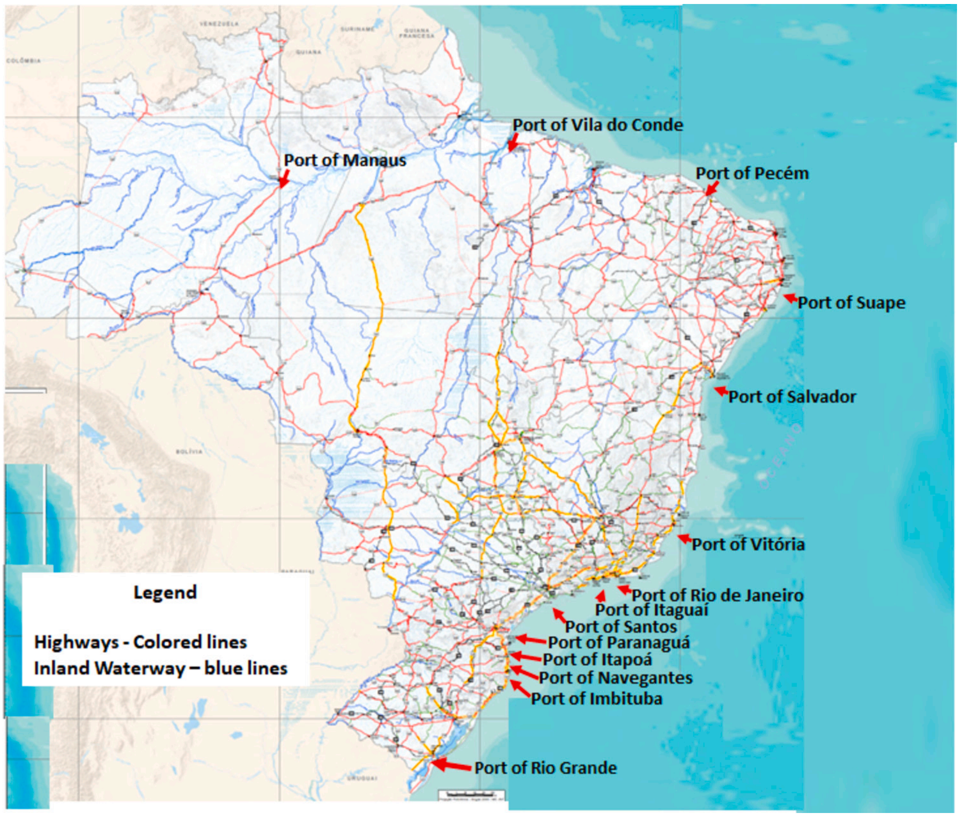

Fig. 3. Brazilian Multimodal Map (Source: DNIT, 2024).

Region	State	State Name	#Cities
Central-West	DF	Destrito Federal	1
Central-West	GO	Goiás	23
Central-West	MT	Mato Grosso	13
Central-West	MS	Mato Grosso do Sul	8
North	AC	Acre	2
North	AP	Amapá	2
North	AM	Amazonas	1
North	PA	Pará	34
North	RO	Rondônia	6
North	RR	Roraima	1
North	TO	Tocantins	5
Northeast	AL	Alagoas	9
Northeast	BA	Bahia	43
Northeast	CE	Ceará	36
Northeast	MA	Maranhão	21
Northeast	PB	Paraíba	10
Northeast	PE	Pernambuco	32
Northeast	PI	Piauí	5
Northeast	RN	Rio Grande do Norte	9
Northeast	SE	Sergipe	7
South	PR	Paraná	36
South	RS	Rio Grande do Sul	45
South	SC	Santa Catarina	31
Southeast	ES	Espírito Santos	11
Southeast	MG	Minas Gerais	72
Southeast	RJ	Rio de Janeiro	38
Southeast	SP	São Paulo	136
		Total	637

Fig. 4. Brazilian Regions, States and Cities per State (Source: Authors).

terminals were obtained from the Brazilian National Waterway Transport Agency (ANTAQ, 2024). Depots near both container and barge terminals were identified using Google Maps.

Each node was georeferenced, and the road distances between cities, as well as the distances between cities and container terminals, cities and barge terminals, and between barge terminals and container terminals, were calculated using the OpenStreetMap API (OSM, 2024). This process, illustrated in Fig. 5, resulted in a super network comprising 637 cities, 18 container terminals, 17 depots, and 8 barge terminals, totaling 680 nodes.

The calculation of CO_2eq emissions employs the well-to-wake (WtW) approach, which accounts for both the production (well-to-tank) and consumption (tank-to-wake) phases of fuel use. For road transportation, emission parameters are derived from the guidelines provided by EPE

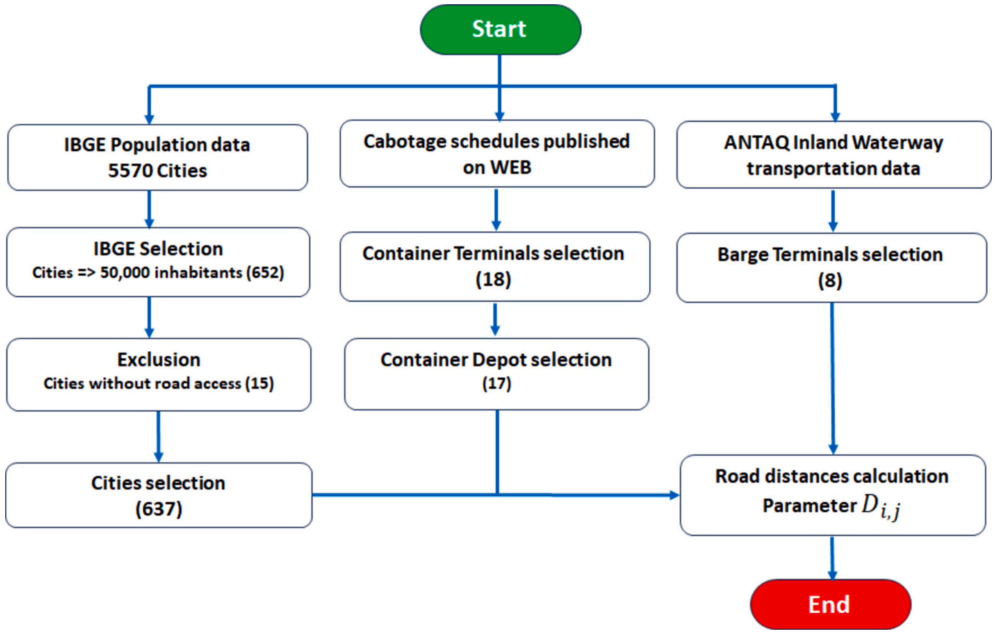

Fig. 5. Process for Establishing the Nodes in the Super Networks (Source: Authors).

(2022), where the diesel fuel energy content is specified as 35,52 MJ/l and its corresponding WtW emission factor is 86,50 gCO_2eq/MJ. For waterway and cabotage transportation modes, the emission parameters are based on the standards outlined in the International Maritime Organization's Resolution MEPC.391(81) (IMO, 2024). The detailed calculation of Marine Diesel Oil (MDO) and Very Low Sulfur Fuel Oil (VLSFO) parameters is provided in Appendix 1. These references offer the necessary coefficients and factors for a comprehensive estimation of GHG emissions across the entire fuel lifecycle for each transport mode, thereby enabling an assessment of their environmental impact.

b) Arcs Data – Road Transportation

The road transportation arcs represent the connections between cities, container terminals, and barge terminals via highways. This study considers two scenarios: one including the BR-319, a planned highway intended to connect the states of Amazonas and Roraima to the rest of Brazil, excluding Amapá, and one excluding it. Table 1 presents the arcs of the road transportation mode, categorized by arc type.

The costs associated with the road transportation arcs were calculated using an Excel worksheet, based on Eq. (1). The parameter values used in these calculations are detailed in Table 2, and the distances $D_{i,j}$ were obtained through the OpenStreetMap API (OSM).

In Brazil, according to Law 12,619/2012, drivers are entitled to an 11-h rest period for every 24 h of work, as well as a one-hour break for meals (Brasil, 2012). Therefore, the application of this law results in a driving time of 11 h per day. Assuming an average speed of 65 km/h, a heavy vehicle covers a distance of 715 km per day.

For example, the cost of the road transportation arc between the cities of Campinas, SP, and Fortaleza, CE, with a distance of 2.907 km, is BRL 22.226. This cost is composed of a basic freight charge of BRL 20.883, a transit time of 4,1 days with an associated transit time cost of BRL 401, and CO_2eq emissions of 2,6 tons, resulting in an emission cost of BRL 942.

Table 1
Road Transportation Arcs (Source: Authors).

Road Transportation Arcs			
Type	Arc Set	Quantity	Remarks
City to City	A_{CY-CY}	366.766 364.234	With BR-319 Without BR-319
City to/from Barge Terminal	$A_{CY-BT} \cup A_{BT-CY}$	7.604	
City to/from Container Terminal	$A_{CY-CT} \cup A_{CT-CY}$	20.264	
Barge Terminal to/from Container Terminal	$A_{BT-CT} \cup A_{CT-BT}$	198	
City to/from Depot	$A_{CY-DP} \cup A_{DP-CY}$	1.274	

Table 2
Eq. (1) Parameters (Source: Authors).

Eq. (1) Parameters			
Parameter	Value	Unit	Source
$D_{i,j}$	various	km	OSM (2024)
Tcd	60,684	BRL/km	ANTT 2 (2024)
Tcc	518,35	BRL/km	ANTT 2 (2024)
d	715	km/day	Brasil (2012)
M_R	15	%	JSL, 2024
v	200.000	BRL	Assumed
i	0,0005	%/day	Assumed
F_c^D	0,28	liters/km	CETESB (2021)
F_e^D	35,52	MJ/l	EPE (2022)
F_f^D	86,50	gCO2eq/MJ	EPE (2022)
Cp	356,2	BRL/tCO2e	Reuters (2024)

c) Arcs Data – Inland Waterway Transportation

The barge terminals considered in this study are located in the Amazon Hydrographic Region and the South Atlantic Hydrographic Region, as depicted in Fig. 6.

The costs associated with the inland waterway transportation arcs were calculated using an Excel worksheet, based on Eqs. (2) and (3). The parameter values used in these calculations are detailed in Table 3, while the distance $D_{i,j}$ for the 32 arcs generated by the 7 barge terminals are provided in Appendix 1.

For example, the cost of the inland waterway transportation arc between the barge terminals of Belém, PA and Santana, AP, with a distance of 476 km, is BRL 3.752. This cost is composed of a basic freight charge of BRL 3.375, a transit time of 2,5 days with an associated transit

Fig. 6. Barge Terminals Locations (Source: Authors).

Table 3
Inland Water Transportation Mode Cost Parameters (Source: Authors).

Eqs. (2) and (3) Parameters			
Parameter	Value	Unit	Source
$D_{i,j}$	Various	km	Appendix 2
S^u	206	Km/day	Grupo Chibatão (2024)
S^d	275	Km/day	Grupo Chibatão (2024)
Dc	1.350	BRL/day	Grupo Chibatão (2024)
v	200.000	BRL	Assumed
i	0,0005	%/day	Assumed
F_c^M	35,62	tons/day	Grupo Chibatão (2024)
F_e^M	36,3	MJ/l	Appendix 1
F_f^M	92,78	gCO_2eq/MJ	Appendix 1
Cp	356,2	BRL/tCO_2eq	Reuters (2024)
h	400	BRL	Grupo Chibatão (2024)

time cost of BRL 250, and CO_2eq emissions of 0,357 tons, resulting in an emission cost of BRL 127.

d) Arcs Data – Cabotage Transportation

Based on the cabotage companies' published schedules, this study considers specific ports and container terminals, as detailed in Table 4. This selection is integral to the analysis as it represents the key nodes within the cabotage super network.

In August 2024, the four cabotage companies considered in this study deployed a total of 27 ships across 14 distinct services, categorized as follows:

- Aliança: Deployed 9 ships, offering the services ALCT 1, ALCT 2, ALCT 3, ALCT 4, and ALCT 5.

Table 4
Selected Container Terminals (Source: Authors).

Container Terminal	Port	State
Porto Chibatão	Manaus	AM
Super Terminais	Manaus	AM
Tecon Salvador	Salvador	BA
APMT Pecém	Pecém	CE
TVV	Vitória	ES
Tecon Vila do Conde	Vila do Conde	PA
Tecon Suape	Suape	PE
TCP	Paranaguá	PR
Sepetiba Tecon	Itaguaí	RJ
ICTSI Rio	Rio de Janeiro	RJ
Multi Rio	Rio de Janeiro	RJ
Tecon Rio Grande	Rio Grande	RS
Tecon Imbituba	Imbituba	SC
Porto Itapoá	Itapoá	SC
Portonave	Navegantes	SC
Brasil Terminal	Santos	SP
DP World Santos	Santos	SP
Tecon Santos	Santos	SP

- Log-In: Also deployed 9 ships, providing the services Serviço Atlântico Sul (SAS), Serviço Shuttle Rio (SSR), Serviço Expresso Amazonas (SEA), Shuttle Service Navegantes (SSN), Serviço Manaus (SMN), and Feeder Shuttle Service (FSS).
- Mercosul Line: Deployed 5 ships, operating the services Plata and Braco.
- Norcoast: Deployed 4 ships, operating the service Amazonas.

Aliança and Log-In operate in alliance, with several shared services:

- Aliança's ALCT 1 corresponds to Log-In's Serviço Manaus (SMN).
- Aliança's ALCT 3 corresponds to Log-In's Serviço Expresso Amazonas (SEA).
- Aliança's ALCT 4 corresponds to Log-In's Serviço Shuttle Rio (SSR).

Additionally, Log-In and Mercosul Line operate in alliance, with Log-In's Serviço Atlântico Sul (SAS) being the same service as Mercosul Line's Plata.

The ports of call and call sequences for these services are detailed in Appendix 3 and consolidated in Table 5, which presents the number of ships per service and cabotage company, the average ship capacity per service, and the respective ship class. This information is used to determine the daily operational cost of the ships, and the costs associated with port calls. Detailed ship data is available in Appendix 4.

The calculation of costs associated with cabotage transportation arcs necessitates a multifaceted approach. Initially, theoretical proformas are developed for each cabotage service based on their published schedule data, including Estimated Time of Arrival (ETA), Estimated Time of Berthing (ETB), and Estimated Time of Sailing (ETS).

Next, the ships deployed on each service and their respective capacities in TEUs are determined, enabling the calculation of average ship capacity per service. This average capacity is then used to derive daily ship costs and port call costs, which depend on the ship class. Marine Diesel Oil (MDO) consumption parameters for port operations and voyages are obtained from a cabotage company, while Very Low Sulfur Fuel Oil (VLSFO) consumption is calculated based on ship speed, which is derived from ETB, ETS, and port distances. The methodology also accounts for two hours of port channel navigation at a speed of 10 knots in VLSFO consumption calculations.

Finally, slot cost, transit times, and emissions factors are computed, and the cabotage arcs are calculated, incorporating terminal handling charges. This comprehensive approach, as shown in Fig. 7, ensures a thorough analysis of cabotage transportation costs, incorporating various critical factors that influence the overall cost structure within the super network model.

The service proformas for each cabotage company service were developed by computing Eqs. (5), (6), (7), and (8) using an Excel worksheet, applying the parameters outlined in Table 6 to calculate key metrics such as slot costs, voyage transit times, transit times between container terminals, fuel consumption, and CO_2eq emissions. This process generated the cabotage arcs A_{CT-CT}, along with the base freight,

Table 5
Cabotage Companies Services Operational Data (Source: Authors).

	Cabotage Companies Services Vessels						
Services	Aliança	Log-In	Mercosul Line	Norcoast	Total	Average Operational Capacity (TEU)	Vessel Class
AL ALCT 1 - LG SMN	4	0	0	0	4	3.056	4.000
Aliança ALCT 2	3	0	0	0	3	4.000	4.500
AL ALCT 3 - LG SEA	1	3	0	0	4	2.247	3.000
AL ALCT 4 - LG SSR	0	1	0	0	1	1.360	2.000
Aliança ALCT 5	1	0	0	0	1	1.392	2.000
Log-In SSV	0	1	0	0	1	2.185	3.000
Log-In SSN	0	1	0	0	1	2.526	3.000
Log-In SAS - Mercosul Line Plata	0	3	1	0	4	2.244	3.000
Mercosul Line Braco	0	0	4	0	4	2.185	3.000
Norcoast Amazonas	0	0	0	4	4	2.806	3.500
Total	9	9	5	4	27	2.400	

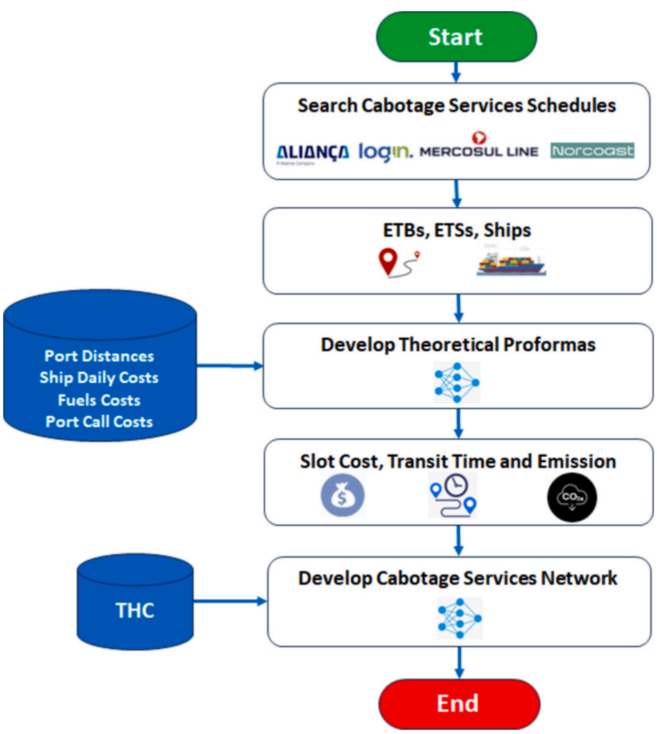

Fig. 7. Cabotage Arc Cost Calculation Methodology (Source: Authors).

Table 6
Cabotage Transportation Mode Cost Parameters (Source: Authors).

Eqs. (5), (6), (7) and (8) Parameters			
Parameter	Value	Unit	Source
$ETA_{s,i}$	As per Appendix 5	–	
$ETB_{s,i}$	As per Appendix 5	–	Aliança, Log-In 1, Mercosul Line and Norcoast (2024)
$ETS_{s,i}$	As per Appendix 5	–	
$D_{i,i+1}$	As per Appendix 6	Nautical miles	ANTAQ (2024)
$S^{PC}_{s,i}$	As per Appendix 7	USD	Cabotage Company
S^{DC}_{s}	As per Appendix 8	USD/day	
S^{TEU}_{s}	As per Table 5	TEU	Authors
F^{MC}	813	USD/ton	Shipandbunker (2024)
F^{MRP}	5,0	ton/day	Cabotage Company
F^{MRV}	3,5	Ton/day	
F^{VC}	601,5	USD/ton	Shipandbunker (2024)
k_1	0,006754	–	Yao et al., 2012
k_2	37,23	Ton/day	Soares, 2022
F^{M}_{e}	42,7	MJ/ton	Appendix 1
F^{M}_{f}	92,78	gCO2eq/ MJ	Appendix 1
F^{V}_{e}	40,2	MJ/ton	Appendix 1
F^{V}_{f}	94,26	gCO2eq/ MJ	Appendix 1
ROE	5,00	BRL/USD	Assumed
THC_i	As per Appendix 9	BRL	Web search
THC_j	As per Appendix 9	BRL	Web search
M_C	15	%	Log-In, 2024
v	200.000	BRL	Assumed
i	0,0005	%/day	Assumed
Cp	356,2	BRL/ tCO_2eq	Reuters (2024)

inventory in transit cost, CO_2eq emissions cost, and arc total cost for each cabotage service, forming the cabotage transportation networks.

The number of arcs, which depends on each service's proforma, varies across the cabotage companies. Specifically, Aliança generates 128 arcs, Log-In produces 102 arcs, Mercosul Line creates 52 arcs, and Norcoast contributes 20 arcs, resulting in a total of 302 A_{CT-CT} (arcs)

Table 7 summarizes the key parameters for the cabotage services, highlighting several important insights:

- Services with a voyage transit time of 7 days (ALCT 4, ALCT 5, Log-In SSR, SSN, and FSS) are feeder services that deploy just one ship. These services have the lowest slot costs among all the cabotage services, reflecting their shorter routes and more frequent rotations.
- The Aliança ALCT 2 service benefits from a lower slot cost due to the average ship operational capacity of 4.000 TEU, which is the highest among all the services. The larger capacity allows for more efficient cost distribution across the available slots.
- Services calling at the Manaus port (ALCT 1, Log-In SEA and SMN, Mercosul Line Braco, and Norcoast Amazonas) exhibit slot costs for a 40-ft container ranging from BRL 5423 (Aliança) to BRL 6902 (Mercosul Line). This variation in slot costs results in distinct cost levels for serving the same market, highlighting differences in operational efficiencies and cost structures among the services targeting the Manaus market.

These observations underscore the diverse operational strategies and cost structures within the Brazilian cabotage market, reflecting the complexities of serving different routes and markets with varying ship capacities, routes and service frequencies.

For example, the cost of the cabotage transportation arc between the Tecon Santos terminal at the Port of Santos, SP, and the APMT terminal

Table 7
Cabotage Services Key Parameters.

Cabotage Service	Voyage Transit Time (days)	Operational Capacity (TEU)	Slot Cost 40′ (BRL)	Emission 40′ (tCO_2eq/day)
Aliança ALCT 1	28,0	3.056	5.423	0,12
Aliança ALCT 2	21,0	4.000	3.058	0,09
Aliança ALCT 3	28,0	2.247	6.710	0,17
Aliança ALCT 4	7,0	1.360	2.192	0,19
Aliança ALCT 5	7,0	1.392	2.040	0,22
Log-In SAS	28,0	2.244	6.273	0,15
Log-In SSR	7,0	1.360	2.192	0,19
Log-In SEA	28,0	2.247	6.710	0,17
Log-In SSN	7,0	2.526	1.114	0,08
Log-In SMN	28,0	3.056	5.423	0,12
Log-In SSV	7,0	2.185	1.104	0,08
Mercosul Line Plata	28,0	2.244	6.273	0,15
Mercosul Line Braco	28,0	2.185	6.902	0,17
Norcoast Amazonas	28,0	2.806	5.731	0,14

at the Port of Pecém, CE, for Aliança's ALCT 1 service is BRL 10.302. This cost is composed of a basic freight charge of BRL 8.801, a transit time of 10,5 days with an associated transit time cost of BRL 1.045,8, and CO_2eq emissions of 1033 tons, which correspond to an emission cost of BRL 367,9.

In comparison, for Mercosul Line Braco service, the arc cost between the DP World Santos terminal at the Port of Santos, SP, and the APMT terminal at the Port of Pecém, CE, is BRL 12.186. This cost comprises a basic freight charge of BRL 10.541, a transit time of 10.9 days with an associated transit time cost of BRL 1.091,7, and CO_2eq emissions of 1552 tons, which correspond to an emission cost of BRL 552,8.

These examples highlight the differences in cost structures between the two services, reflecting variations in freight charges, transit times, and environmental impacts. The higher costs associated with Mercosul Line are primarily due to its higher basic freight charge related to a higher 40′ slot cost than Aliança and greater CO_2eq emissions, which contribute to the overall arc cost.

In modeling cabotage transportation mode's networks, incorporating both road and waterway arcs, this study proposes a novel approach to represent transit times more accurately. A two-day augmentation is applied to cabotage arcs A_{CT-CT} transit time, serving a dual function: firstly, to account for liner service-specific operations such as container handling, container deadline and customs processes (Notteboom, 2006); secondly, to represent transshipment delays when two cabotage arcs are consecutive. This method aligns with Rodrigue and Notteboom's (2009) emphasis on terminal operations in global supply chains. By implementing this dual-purpose time addition, the model achieves a better representation of both direct maritime transit and transshipment scenarios, enhancing its fidelity in simulating door-to-door container movements. This approach contributes to a more comprehensive understanding of transit times in liner shipping networks. These two days count for cabotage arcs' inventory in transit cost but not for CO_2eq emissions cost.

It is also important to note that the transportation of empty containers from depots to cities (as part of the cabotage pre-carriage transportation) and from cities to depots (as part of the cabotage on-carriage transportation) does not contribute to the total cabotage transit time or associated inventory in transit cost because there is no cargo inside the containers.

5.2. Application

Two Python algorithms, using the Floyd-Warshall approach, were used to solve the Minimum Cost Paths problem in both road and cabotage transportation networks. The analysis covered two road transportation mode super networks and four cabotage transportation mode super networks, each tailored to a specific cabotage company. The results from these super networks were compiled into a database for comparative analysis. Table 8 presents the configuration of the six super networks.

- SN 1 represents the road transportation mode super network with BR 319 in operation, with 645 nodes and 374.402 arcs.
- SN 2 represents the road transportation mode super network without BR 319, with 645 nodes and 371.804 arcs.
- SN 3 represents the cabotage transportation mode super network for Aliança, with 680 nodes and 29.496 arcs.
- SN 4 represents the cabotage transportation mode super network for Log-In, with 680 nodes and 29.486 arcs.
- SN 5 represents the cabotage transportation mode super network for Mercosul Line, with 680 nodes and 29.416 arcs.
- SN 3 represents the cabotage transportation mode super network for Aliança, with 680 nodes and 29.391 arcs.

It is important to note that the cabotage transportation mode's super networks do not include cities to cities arcs (A_{CY-CY}). This exclusion forces the algorithm to seek paths that rely on cabotage services rather than defaulting to more direct road connections, thereby providing a more accurate representation of the cabotage network's operational dynamics.

Adapting established algorithms for complex super networks is a frequent practice in network science and operations research. As noted by Ahuja et al. (1993), network flow models offer a solid framework for analyzing intricate network problems. In the case of a super network consisting of roadway, waterway, and cabotage arcs, modifying classical

Table 8
Cabotage Super Networks Configurations (Source: Authors).

Nodes and Arcs	Cabotage Super Networks Configuration SN 1	SN 2	SN 3	SN 4	SN 5	SN 6
Nodes CY	637	637	637	637	637	637
Nodes BT	8	8	8	8	8	8
Nodes CT			18	18	18	18
Nodes DP			17	17	17	17
Arcs CY-CY with BR319	366.766					
Arcs CY-CY without BR319		364.234				
Arcs CY-BT and BT-CY	7.604	7.604	7.604	7.604	7.604	7.604
Arcs CY-CT and CT-CY			20.264	20.264	20.264	20.264
Arcs BT-BT	32	32	32	32	32	32
Arcs BT-CT and CT-BT			196	196	196	196
Arcs DP-CY and CY-DP			1.274	1.274	1.274	1.274
Arcs CT-CT Aliança			128			
Arcs CT-CT Log-In				102		
Arcs CT-CT Mercosul Line					52	
Arcs CT-CT Norcoast						20
Total Nodes	**645**	**645**	**680**	**680**	**680**	**680**
Total Arcs	**374.402**	**371.870**	**29.498**	**29.472**	**29.422**	**29.390**

algorithms is necessary to account for specific constraints and operational requirements. This approach aligns with Ziliaskopoulos and Mahmassani (1996), who adapted shortest path algorithms for transportation networks with turn penalties and prohibitions. Similarly, Pallottino and Scutellà (1998) emphasized the need to tailor standard algorithms for various transportation scenarios.

By building on the Floyd-Warshall algorithm and incorporating additional constraints to capture the characteristics of inland waterway and cabotage operations, this study follows a well-established tradition of customizing algorithms to solve domain-specific challenges. This method leverages the efficiency of classical algorithms while integrating domain expertise, offering a more effective solution to the super network problem.

The average run time for each of the six super networks using the algorithm was 15 min with a computer with Intel(R) Core(TM) i7-9750H CPU @ 2.60GHz 2.59 GHz with 32,0 GB RAM.

5.3. Results

In addressing the research questions, this section analyzes the competitiveness of cabotage transportation mode compared to road transportation mode in Brazil:

(a) For which city pairs in Brazil does cabotage transportation mode demonstrate superior competitiveness compared to road transportation mode, considering freight rates, in-transit inventory costs, and CO2eq emissions costs?

(b) What is the correlation between the competitiveness of cabotage transportation mode and the aggregate pre- and on-carriage distances compared to the direct road transportation mode distances between origin and destination cities?

The analysis answers these questions by comparing the results from the six super network models developed in this study. These models evaluate the minimum-cost paths for both transportation modes, incorporating key variables such as freight costs, environmental impact (CO_2eq emissions and costs), and in-transit inventory costs.

The following subsections detail the competitiveness of cabotage compared to road transport based on city pair distances, environmental impacts, and regional variations.

The outputs from the two algorithms were consolidated in an Excel file to facilitate a comparison of costs and emissions between the road and cabotage transportation modes. The analysis encompasses 369.306 paths from origin cities to destination cities, excluding intra-state city pairs (Table 9). These paths are used to evaluate the impact of the BR-319 highway on the road transportation mode and to compare road transportation (without BR-319) with cabotage transportation for each cabotage company.

5.3.1. BR319 impact on cabotage

In this section, we begin to address the first research question: ‘For which city pairs does cabotage demonstrate superior competitiveness compared to road transportation?’. Specifically, we examine how the potential operation of BR-319 might affect the competitiveness of cabotage for city pairs in the North and Northeast regions.

If the BR-319 highway becomes operational, connecting Manaus (AM) and Boa Vista (RR) to other regions via road instead of relying on waterways (with the exception of connections to cities in Amapá), a marginal reduction in road transportation costs is expected for the Central-West, South, and Southeast regions. A cost reduction ranging from BRL 3.091 to BRL 3.100 is anticipated for transport to and from Acre (AC) and Rondônia (RO) in the North region. However, no changes in road transportation costs are expected for the Northeast region.

These marginal reductions in road transportation costs are unlikely to significantly impact the competitiveness of cabotage transportation for the states of Amazonas (AM) and Roraima (RR), as depicted in Fig. 8.

5.3.2. Cabotage transportation mode competitiveness analysis

This study aimed to identify the competitive regions for cabotage transportation by analyzing the correlation between intercity road distances and the pre- and on-carriage distances from cities to the ports utilized for cabotage. The analysis focused on paths where cabotage costs were at least 10 % lower than road transportation costs. This 10 % threshold was chosen as it represents a significant cost advantage, which is typically seen as the tipping point at which road transportation customers would be willing to switch to cabotage. The analysis was conducted separately for the networks of four cabotage companies: Aliança, Log-In, Mercosul Line, and Norcoast.

The data encompasses a total of 369.306 road transportation mode’s paths between the North (NO). Northeast (NE), South (SO), Southeast (SE) and Central-West (CW) regions. Aliança emerges as the market leader with 52.687 competitive paths, constituting 14,3 % of total paths. Log-In follows with 33.772 paths (9,1 % of total), Mercosul Line with 27.555 (7,5 % of total), and Norcoast with 25.898 (7.0 % of total).

Cabotage competitiveness is concentrated in long-distance, interregional paths, particularly those connecting the Northeast, South, and Southeast regions. Notably:

- Northeast-South path: Aliança leads with 67.3 % competitiveness, followed by Log-In (38.1 %), Mercosul Line (37.9 %), and Norcoast (33.5 %).
- South-Northeast path: Aliança again dominates with 65.4 %, followed by Log-In (42.3 %), Mercosul Line (41.2 %), and Norcoast (36.5 %).
- Northeast-Southeast path: Aliança maintains leadership with 23.1 %, followed closely by Log-In (17.1 %), Norcoast (11.0 %), and Mercosul Line (10.8 %).
- Southeast -Northeast path: Aliança maintains leadership with 19,8 %, followed closely by Log-In (17.2 %), Mercosul Line (12,5 %) and Norcoast (12,1 %),

All companies show minimal to no competitive presence in several regions:

- Central-West: Almost no competitive paths to or from this region, with only Aliança showing a negligible 0.3 % competitiveness on the Northeast-Central-West path and 0.1 % on the Central-West-Northeast path.
- Intra-regional paths: No competitive paths within CW-CW, NE-NE, N—N, SE-SE, and S—S.

Table 9
Road Transportation Mode - Paths per Region Pair (Source: Authors).

Road Transportation Mode - Paths per Region Pair						
Region	Central-West	North	Northeast	South	Southeast	Total
Central-West	1.262	2.295	7.740	5.040	11.565	27.902
North	2.295	1.374	8.772	5.712	13.107	31.260
Northeast	7.740	8.772	24.638	19.264	44.204	104.618
South	5.040	5.712	19.264	8.262	28.784	67.062
Southeast	11.565	13.107	44.204	28.784	40.804	138.464
Total	**27.902**	**31.260**	**104.618**	**67.062**	**138.464**	**369.306**

Impact on Road Transportation Mode Cost with BR319 (BRL)													
State	AC	AM	RR	MG	RJ	SP	PR	SC	RS	GO	MS	MT	RO
AC	0	-841	-860	0	0	0	0	0	0	0	0	0	0
AM	-3.091	0	0	-2	-4	-144	-285	-586	-25	-63	-493	-808	-3.106
RR	-3.099	0	0	-2	-4	-154	-294	-596	-26	-65	-496	-817	-3.116
MG	0	-271	-278	0	0	0	0	0	0	0	0	0	0
RJ	0	-507	-524	0	0	0	0	0	0	0	0	0	0
SP	0	-841	-861	0	0	0	0	0	0	0	0	0	0
PR	0	-842	-861	0	0	0	0	0	0	0	0	0	0
SC	0	-840	-860	0	0	0	0	0	0	0	0	0	0
RS	0	-842	-860	0	0	0	0	0	0	0	0	0	0
GO	0	-182	-186	0	0	0	0	0	0	0	0	0	0
MS	0	-842	-862	0	0	0	0	0	0	0	0	0	0
MT	0	-581	-596	0	0	0	0	0	0	0	0	0	0
RO	0	-841	-860	0	0	0	0	0	0	0	0	0	0

Fig. 8. Impact on Road Transportation Mode with BR-319 (Source: Authors).

- Southeast-South and South-Southeast paths: Only Log-In shows minimal competitiveness (1.1 % and 0.7 % respectively).

The Northern region experiences limited competition, with Aliança maintaining a dominant presence, primarily through its ALCT 5 service, which connects the states of Pará and Ceará. Aliança utilizes the Port of Pecém as a transshipment hub, further enhancing connectivity between Pará and the southeastern and southern states.

- North-Northeast: Aliança (7.5 %), Log-In (4.0 %), Norcoast (3.4 %), Mercosul Line (2.1 %)
- North-Southeast: Aliança (13.3 %), Log-In (4.6 %), Mercosul Line (3.7 %), Norcoast (3.6 %)
- North-South: Aliança (33.8 %), Norcoast (5.4 %), Log-In (5.3 %), Mercosul Line (4.7 %)

This analysis highlights the concentration of cabotage competitiveness along specific long-distance routes, particularly between the Northeast, South, and Southeast regions. The data also reveals significant variations in market presence among the four companies in Brazil's cabotage sector, with Aliança consistently demonstrating the strongest competitive position across most paths, as depicted in Fig. 9.

The competitiveness of cabotage companies is strongly correlated with the distances covered by road transportation between origin and destination cities. The analysis reveals that, excluding feeder services, the minimum road distance at which cabotage becomes competitive varies across the companies: Aliança at 1.800 km, Log-In at 2.200 km, Mercosul Line at 2.419 km, and Norcoast at 2.508 km. Aliança and Log-In, with more extensive networks, demonstrate greater competitiveness compared to Mercosul Line and Norcoast. However, all four companies

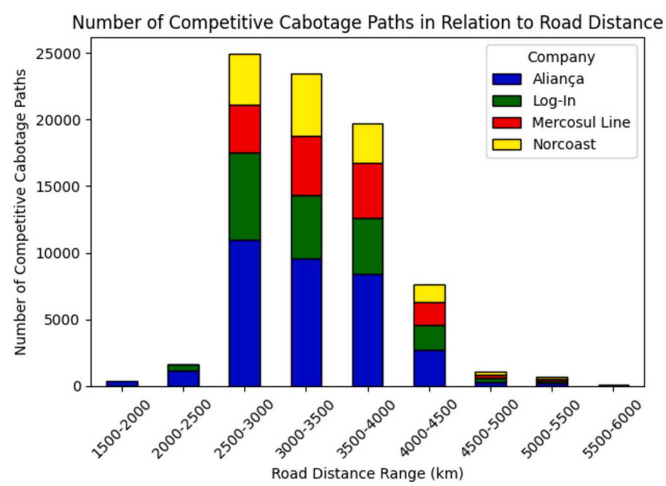

Fig. 10. Number of Cabotage Competitive Paths in relation to Road Transportation Mode Distance (Source: Authors).

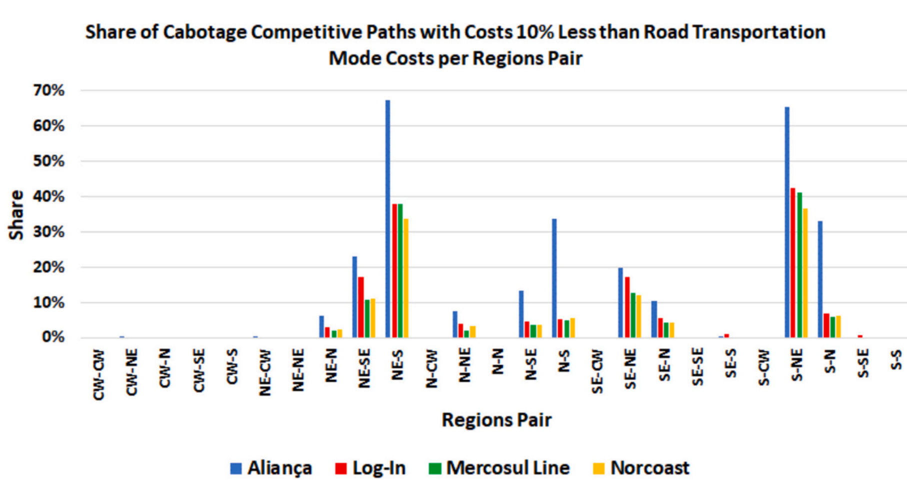

Fig. 9. Share of Cabotage Competitive Paths with Costs 10 % Less than Road Transportation Mode Costs per Region Pair (Source: Authors).

follow a similar pattern, with their competitive advantage concentrated in specific road transportation mode distance ranges, as shown in Fig. 10.

The analysis further underscores that as road transportation distances increase, cabotage becomes a more viable option for reaching cities located further inland. This, in turn, leads to longer pre- and on-carriage distances for the cabotage transportation mode, reinforcing the importance of multimodal integration in logistics planning for the cabotage companies.

In the example presented in Section 3, where the city of Campinas, located in the state of São Paulo, serves as the origin and the city of Macapá, in the state of Amapá, as the destination, the analysis reveals the following transportation paths and associated costs:

- For road transportation mode, the path " Campinas - SP -> Barge Terminal Vila do Conde -> Barge Terminal Santana -> Macapá - AP" incurs a cost of BRL 24.626.
- The Aliança cabotage path " Depot Santos -> Campinas - SP -> Tecon Santos -> APMT Pecém -> Tecon Vila do Conde -> Barge Terminal Vila do Conde -> Barge Terminal Santana -> Macapá - AP -> Depot Santana" offers a reduced cost of BRL 23.629, reflecting a 4,0 % cost saving.
- Log-In's cabotage path " Depot Santos -> Campinas - SP -> BTP -> Porto Chibatão -> Barge Terminal Manaus -> Barge Terminal Santana -> Macapá - AP -> Depot Santana" presents a cost of BRL 24.192, representing a 1,8 % reduction.
- The Mercosul Line path " Depot Santos -> Campinas - SP -> DP World Santos -> Porto Chibatão -> Barge Terminal Manaus -> Barge Terminal Santana -> Macapá - AP -> Depot Santana" is associated with a cost of BRL 26.245, showing a 6,6 % increase.
- Norcoast's route " Depot Santos -> Campinas - SP -> Tecon Santos -> Super Terminais -> Barge Terminal Manaus -> Barge Terminal Santana -> Macapá - AP -> Depot Santana" incurs a cost of BRL 24.658, marking a 0,1 % increase.

Campinas, located in the Southeast region, and Macapá, in the North, are situated in regions where cabotage demonstrates superior competitiveness over road transportation. However, for this specific city pair, cabotage is not competitive, despite the road transportation distance of 3.265 km falling within the competitiveness range for all the companies analyzed. This example highlights that exceptions may exist within the cabotage competitiveness region.

In this case, the higher inland waterway cost for cabotage significantly reduces its competitiveness. Specifically, the on-carriage cost for cabotage from Barge Terminal Manaus (AM) to Barge Terminal Santana (AP) is BRL 7.271, while the corresponding on-carriage cost for road transportation from Barge Terminal Vila do Conde (PA) to Barge Terminal Santana (AP) is much lower, at BRL 4.152. This discrepancy underscores a key factor contributing to the reduced competitiveness of cabotage for this particular city pair, even though the road distance falls within the typically competitive range for cabotage.

The analysis further reveals that for Aliança, there are 12.006 paths where the road transportation distance exceeds 3.500 km, but in 6.714 of these cases, cabotage is not competitive. This finding suggests that while cabotage becomes increasingly competitive beyond a certain road transportation mode distance threshold, it is not universally competitive for all paths exceeding this distance. Although cabotage companies may offer cost efficiencies for many routes beyond the 2.500 km mark (Norcoast minimum distance), other factors - such as specific origin and destination regions - affect its competitiveness. The distribution of noncompetitive cabotage paths is shown in Fig. 11.

When comparing the analysis results with ANTAQ (2024) statistics for the period from January to July 2024, during which cabotage throughput reached 761.520 TEUs, several key observations can be made (Table 10). Transports between the South and Southeast regions, as well as within these regions, accounted for 234.725 TEUs, representing 30,8 % of the total throughput. This significant share is primarily attributed to cabotage feeder services supporting Deep Sea Services. The remaining region pairs, contributing a total of 526.795 TEUs (69,2 %), align closely with this study's analysis results. This alignment suggests that the cabotage transportation mode's competitiveness region, as identified in the analysis, accurately reflects the actual distribution and effectiveness of cabotage services during this period.

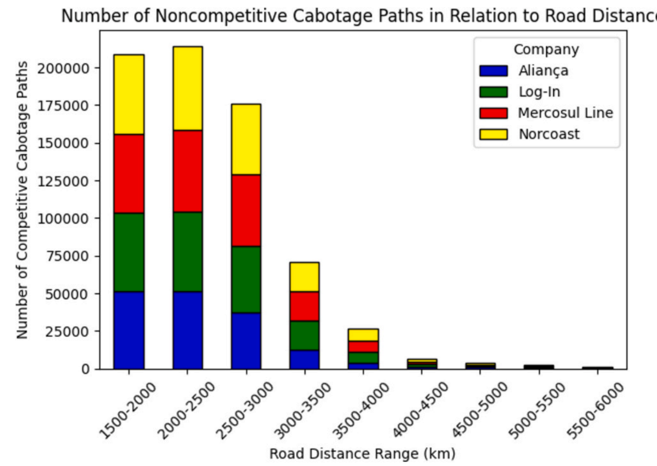

Fig. 11. Number of Noncompetitive Cabotage Paths in Relation to Road Transportation Mode Distance (Source: Authors).

Table 10
Cabotage Throughput Share per Region Pairs JAN-JUL 2024 (Source: Authors).

Cabotage Throughput Share per Region Pairs - JAN-JUL 2024 (%)					
Regions	North	Northeast	South	Southeast	Total Destination
North	0%	6 %	1 %	11 %	19 %
Northeast	3%	5 %	3%	7 %	18%
South	3%	12 %	6 %	3%	24 %
Southeast	7 %	10 %	11 %	11 %	40 %
Total Origin	**14 %**	**34 %**	**21 %**	**32 %**	**100 %**

5.3.3. *Cabotage transportation mode CO_2eq emissions analysis*

This analysis aimed to evaluate the environmental competitiveness of cabotage transportation by examining CO_2eq emissions along paths where cabotage costs were at least 10 % lower than those of road transportation. Emissions for cabotage were compared to road transport emissions for the same origin and destination cities. The analysis was conducted separately for the networks of four cabotage companies: Aliança, Log-In, Mercosul Line, and Norcoast. The calculations assumed the transport of one container per cabotage path, with the corresponding road transport emissions based on a six-axle truck and trailer for the same city pairs.

The results of the CO_2eq emissions analysis show significant environmental benefits for cabotage across all four companies, as depicted in Table 11. Cabotage consistently results in lower emissions, with

Table 11
CO_2eq Emission for Cabotage and Road Transportation Modes (Source: Authors).

CO_2eq Emission (tons)			
Company	Road Paths	Cabotage Paths	Diff.
Aliança	150.225	94.769	-36,9 %
Log-In	96.604	55.892	−42,1 %
Mercosul Line	81.872	46.320	−43,4 %
Norcoast	77.247	44.247	−42,7 %
Average			−41,3%

reductions ranging from 36,9 % to 43,4 % compared to equivalent road transport paths. Specifically, Aliança shows a 36,9 % reduction in CO_2eq emissions, with road transportation mode emitting 150.225 tons, compared to 94.769 tons for cabotage. Log-In, Mercosul Line, and Norcoast demonstrate even greater reductions, with Log-In achieving a 42,1 % reduction, Mercosul Line 43,4 %, and Norcoast 42,7 %.

On average, the shift from road transportation mode to cabotage results in a 41,3 % decrease in CO_2eq emissions. These findings underscore the potential of cabotage as a more environmentally sustainable mode of transportation, offering substantial reductions in greenhouse gas emissions compared to traditional road transportation, suggesting that a greater modal shift could be encouraged through supportive policies, including investment in port infrastructure and incentives for greener shipping technologies.

5.3.4. *Sensitivity analysis*

The sensitivity analysis compares the cost equations for road transport and cabotage, as outlined in Appendix 10. The analysis uses the Aliança ALCT1 service as a base case and applies the following basic parameters:

- The combined distance from the origin city to the loading port and from the discharge port to the destination city is 100 km.
- Average Terminal Handling Charges (THC) at the loading and discharge ports are BRL 988 each.
- Cabotage transit time is 10.5 days.

Eight scenarios were developed to explore the sensitivity of the results to changes in key variables:

- Base Scenario: The analysis is based on the Aliança ALCT1 service data and the basic parameters defined above.
- Scenario 1: Slot costs are reduced by 20 %, reflecting potential savings from lower fuel costs and a favorable exchange rate.
- Scenario 2: Diesel emissions parameters are reduced by 80 %, simulating the use of biodiesel for road transport.
- Scenario 3: Maritime fuel emissions parameters are reduced by 80 %, representing the substitution of traditional marine fuels with biodiesel.
- Scenario 4: The cargo value increases to BRL 500,000, affecting the inventory cost component.
- Scenario 5: The interest rate doubles, increasing the cost of holding inventory in transit.
- Scenario 6: Carbon pricing decreases to BRL 100 per ton of CO_2 equivalent, reducing the cost of emissions.
- Scenario 7: Cabotage transit time increases to 16 days, representing delays or slower service speeds.
- Scenario 8: Slot costs increase by 20 %, THC increases by 20 %, and the interest rate doubles, simulating a general rise in the operational cost base for cabotage.

The sensitivity analysis demonstrates the effect of varying key parameters on the minimum distance threshold at which cabotage becomes more competitive than road transport. The results, depicted in Fig. 12, highlight how changes in operational, environmental, and economic conditions influence cabotage's competitiveness:

- **Base Scenario**: Under the base parameters, cabotage becomes competitive at distances greater than 1616 km. This serves as the benchmark for comparison across all scenarios.
- **Scenario 1 (Reduced Slot Costs)**: Reducing slot costs by 20 % decreases the competitive threshold to 1448 km, a reduction of 10.4 %. This indicates that cost efficiencies in cabotage operations significantly enhance its competitiveness.
- **Scenario 2 (Reduced Diesel Emissions Parameter):** An 80 % reduction in diesel emissions lowers the environmental cost of road transport, slightly increasing the competitive threshold to 1666 km (+3.1 %). This demonstrates the sensitivity of cabotage competitiveness to changes in road transport's environmental impact.
- **Scenario 3 (Reduced Maritime Emissions Parameter):** Reducing maritime fuel emissions by 80 % lowers the competitive threshold to 1568 km (−2.9 %), emphasizing the potential environmental benefits of adopting cleaner fuels in cabotage operations.
- **Scenario 4 (Increased Cargo Value)**: Increasing the cargo value to BRL 500,000 raises the threshold to 1777 km (+10.0 %). Higher cargo values increase inventory holding costs, making cabotage less competitive due to longer transit times.

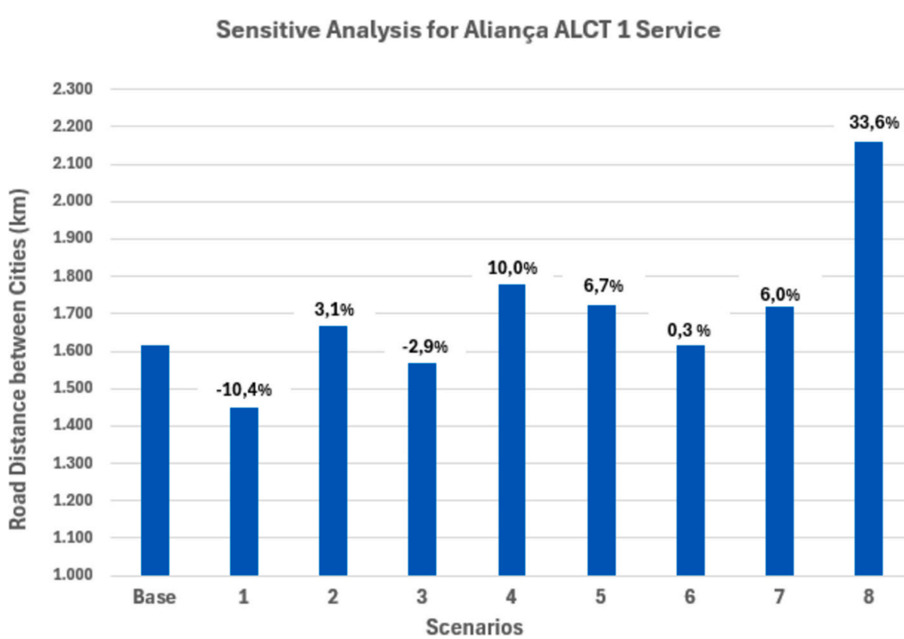

Fig. 12. Sensitive Analysis for Aliança ALCT 1 Service (Source: Authors).

- **Scenario 5 (Higher Interest Rates)**: Doubling the interest rate increases the threshold to 1724 km (+6.7 %), highlighting the sensitivity of inventory costs to financial conditions.
- **Scenario 6 (Lower Carbon Price)**: Reducing the carbon price to BRL 100/tCO2eq has a negligible impact, with the threshold slightly increasing to 1617 km (+0.1 %). This suggests that carbon pricing plays a limited role in the cost structure at current levels.
- **Scenario 7 (Increased Transit Time)**: Increasing cabotage transit time to 16 days raises the threshold to 1719 km (+6.4 %). Delays or slower services reduce the competitiveness of cabotage, reinforcing the importance of operational efficiency.
- **Scenario 8 (General Cost Increases)**: A combined increase in slot costs (+20 %), THC (+20 %), and interest rates (+100 %) results in a significant increase in the competitive threshold to 2159 km (+33.6 %). This scenario highlights the compounded impact of higher costs on cabotage's competitiveness.

5.4. Discussion

The findings of this study offer comprehensive insights into the competitiveness of cabotage transportation mode compared to road transportation mode in Brazil, addressing both research questions.

In relation to the first research question, the analysis demonstrates that cabotage can offer superior competitiveness for specific city pairs, particularly when freight rates, in-transit inventory costs, and CO_2eq emissions are considered. The study identified that cabotage is more competitive on routes where road transportation distances exceed certain thresholds: excluding the feeder services, Aliança shows competitiveness at distances over 1800 km, Log-In at over 2200 km, Mercosul Line at over 2419 km, and Norcoast at over 2508 km. These thresholds highlight cabotage as a viable alternative to road transportation mode, particularly for long-haul routes connecting the regions of North and Northeast to South and Southeast and vice versa. Additionally, the environmental analysis revealed substantial CO_2eq emission reductions, with an average reduction of 41.3 % compared to road transport, further enhancing cabotage's competitiveness from a sustainability perspective.

Regarding the second research question, the study established a clear correlation between cabotage competitiveness and the aggregate pre- and on-carriage distances relative to direct road transportation distances. The analysis indicates that cabotage's competitiveness is influenced not only by the absolute distance between origin and destination cities but also by the pre- and on-carriage distances connecting ports to these cities. As road transportation mode distances increase, cabotage becomes increasingly competitive, even when factoring in the additional distances for connecting cities to ports. This finding underscores the importance of integrated logistics planning and infrastructure development to further enhance cabotage's competitiveness, particularly in regions where road transportation traditionally dominates.

The sensitivity analysis provides key insights into factors shaping cabotage competitiveness. Operational efficiency, including reduced slot costs (Scenario 1) and biodiesel adoption (Scenario 3), significantly enhances cost-effectiveness, emphasizing the importance of cost management and cleaner fuels. Economic conditions, such as cargo value (Scenario 4) and interest rates (Scenario 5), strongly influence competitive thresholds, highlighting the role of financial dynamics.

While carbon pricing (Scenario 6) showed minimal impact, adopting cleaner fuels remains pivotal for improving both environmental and economic performance. Additionally, increased transit times (Scenario 7) reduce competitiveness, underscoring the importance of reliable service schedules. These findings highlight the need for integrated strategies that address operational, economic, and environmental factors to optimize cabotage as a sustainable alternative to road transport.

These results provide valuable insights for policymakers and industry stakeholders seeking to promote cabotage as a sustainable and cost-effective transport mode. Reducing operational costs and transit times, alongside adopting cleaner fuels and mitigating economic volatility, are critical strategies for enhancing cabotage's competitiveness.

In conclusion, cabotage transportation presents a competitive alternative to road transport for certain city pairs in Brazil, especially over longer distances. However, the competitiveness of cabotage is closely tied to the efficiency of the logistics network in managing pre- and on-carriage operations. These insights form a basis for policy recommendations aimed at enhancing cabotage competitiveness, including investments in port infrastructure, rail networks, inland container terminals, and the adoption of sustainable logistics practices. Furthermore, targeted initiatives to reduce slot costs, improve service reliability, and encourage the adoption of low-carbon technologies are essential for maximizing the potential of cabotage as a key component of Brazil's logistics network.

6. Conclusions and future work

This study presents a comprehensive evaluation of Brazilian maritime container cabotage competitiveness within a multimodal transportation network, addressing a notable gap in the extant literature. While previous research has primarily concentrated on the strategic importance of maritime cabotage (Soares, 2022) or its operational challenges (Paixão Casaca et al., 2017; Silveira Junior & Nunes, 2022), this study advances the discourse by providing an in-depth analysis of the interplay between cabotage and road transportation modes. Specifically, it integrates logistics costs, in-transit inventory costs, and CO_2eq emissions and costs into the assessment, thereby offering a holistic and practical perspective on cabotage's end-to-end competitiveness within a multimodal framework.

Unlike traditional studies that analyze transportation modes in isolation, this research adopts a multimodal super network approach that incorporates pre- and on-carriage operations, bridging an important gap in the literature. By evaluating the dynamic interactions between logistics elements, the study provides a more comprehensive understanding of the factors that influence cabotage competitiveness. Moreover, the sensitivity analysis conducted herein introduces a dynamic framework that quantifies the impacts of varying operational, environmental, and economic parameters - such as slot costs, transit times, and carbon pricing - on cabotage's performance. This dual emphasis on methodological innovation and scenario-based analysis positions the study as a significant contribution to both academic research and industry practice.

Through the application of an adapted All Pairs Shortest Path (APSP) algorithm, this study evaluates the minimum-cost paths across a complex multimodal network, offering new insights into the conditions under which maritime cabotage achieves competitive advantage. The findings reveal that cabotage exhibits cost-competitiveness for distances exceeding 1800 km, corroborating the assertions of da Silva et al. (2022) regarding the inherent benefits of maritime transport for long-haul routes. Nonetheless, this study identifies significant variability in competitiveness, contingent upon factors such as pre- and on-carriage distances and regional market dynamics. These nuances contribute to the broader discussion on modal shift potential (Meers and Macharis, 2015; Raza et al., 2020), providing a more granular understanding of cabotage's role in Brazil's logistics framework.

Moreover, this research extends the literature on multimodal network analysis (Chang et al., 2010; Wong et al., 2010) by incorporating a comprehensive cost analysis that includes not only freight rates and in-transit inventory costs but also CO_2eq emissions costs. This integrative approach enables a holistic assessment of cabotage's potential contribution to sustainable logistics, addressing the environmental considerations highlighted by Hjelle (2011) and Chandra et al. (2016).

From a practical standpoint, the findings suggest that logistics planners and shippers in Brazil could achieve significant cost savings and environmental benefits by incorporating cabotage into supply chain strategies, particularly on routes where road transportation distances surpass the identified thresholds. Additionally, the study provides empirical evidence to support policymakers in developing targeted interventions that promote the use of cabotage as part of a balanced transportation matrix.

Future research should explore several key areas. First, this study's identification of a 10 % cost advantage as a tipping point for customers to switch from road to cabotage is a significant practical finding. Future research could investigate the behavioral aspects of shippers' decision-making to validate this threshold further, providing deeper insights into customer preferences. Additionally, the impact of future infrastructural developments, such as port expansions and investments in rail networks, should be quantitatively analyzed to understand their effect on cabotage's competitiveness. Further studies could also investigate how new sustainability policies, such as carbon pricing or incentives for modal shift, might alter the cost structure and environmental benefits of cabotage. Finally, integrating inland terminals and enhanced rail connectivity into the super network model could offer a deeper understanding of how multimodal logistics could further enhance the efficiency and sustainability of Brazil's transportation system.

In this study, several assumptions were made to support the emissions analysis. First, fuel consumption rates were assumed to vary based on the specific distance and duration of each voyage segment, although factors like ship load, weather conditions, and sea currents, which also affect fuel use, were not explicitly modeled. This approach ensures a tailored calculation, while acknowledging that actual fuel consumption may differ due to operational conditions. Additionally, standard well-to-wake (WtW) emission factors for Marine Diesel Oil (MDO) and Very Low Sulfur Fuel Oil (VLSFO) were applied to provide a comprehensive estimate of emissions. Although these factors reflect typical values, variations in fuel quality and engine efficiency could result in deviations in real-world emissions. The carbon price was fixed at BRL 356.2 per ton of CO_2eq, based on Reuters. (2024); however, fluctuations in carbon pricing, driven by policy or market dynamics, could influence the final emissions cost and alter the competitive analysis between cabotage and road transport. Given these assumptions, the study acknowledges that changes in key parameters - such as fuel consumption, emission factors, or carbon pricing - may impact the results. Therefore, also for future research is recommended to explore the sensitivity of these variables to offer a more dynamic and context-specific understanding of cabotage's environmental competitiveness.

In conclusion, this study advances the understanding of Brazilian maritime cabotage's competitive dynamics within a multimodal network, thereby filling a critical gap in the literature. By synthesizing cost structures, environmental impacts, and operational conditions, it contributes to both the theoretical framework of multimodal transportation and the practical optimization of sustainable logistics practices in Brazil.

CRediT authorship contribution statement

Gustavo Adolfo Alves da Costa: Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **André Bergsten Mendes:** Writing – review & editing, Supervision, Resources, Methodology. **José Pedro Gomes da Cruz:** Software.

Declaration of competing interest

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

Appendix A. MDO and VLSFO Emission Parameters

The GHG emission factors are calculated as CO_2 equivalents (CO_2eq) using the global warming potential (GWP) values provided in the Fifth Assessment Report of the IPCC for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The values adopted in this work are the 100-year GWP (GWP100) according to the IPCC report on page 87 (IPCC, 2014), presented in Table 12.

Table 12
Global Warming Potential (Source IPCC, 2014).

Gas	GWP100
CO_2	1
CH_4	28
N_2O	265

The GHG emissions from Well-to-Wake (GHG_{WtW}) are the sum of Well-to-Tank (GHG_{WtT}) and Tank-to-Wake (GHG_{TtW}) emissions for a given fuel and its pathway (IMO, 2024). MEPC.391(81) provides standard WtT values for each fuel pathway, making it necessary to calculate the TtW values using Eq. 23.

$$GHG_{TtW} = \frac{1}{PCI}\left(C_{fCO_2} {*} GWP_{Co_2} + C_{fCH_4} {*} GWP_{CH_4} + C_{fN_2O} {*} GWP_{N_2O}\right) \tag{23}$$

Where,

- C_{fCO_2} is the CO_2 emission conversion factor (gCO_2/g of fully burned fuel) for emissions from combustion and/or the oxidation process of the fuel used by the ship.
- C_{fCH_4} is the CH_4 emission conversion factor (gCH_4/g of fuel delivered to the ship) for emissions from combustion and/or the oxidation process of the fuel used by the ship.
- C_{fN_2O} is the N_2O emission conversion factor (gN_2O/g of fuel delivered to the ship) for emissions from combustion and/or the oxidation process of the fuel used by the ship.
- $GWP_{Co_2}, GWP_{CH_4} e\ GWP_{N_2O}$ are the GWP_{100} values for each gas.

Table 13 presents the GHG_{WtW} values for the fuels VLSFO and MDO using the parameters from MEPC.391(81) and considering the Lower Heating Values (LHV) (MJ/g) of 0,0402 for VLSFO and 0,0427 for MDO.

Table 13
WtW Parameters for MDO and VLSFO (Source: Authors).

GHG Intensity (gCO_2eq/MJ)	VLSFO	MDO
WtT	16.8	17.7
C_{fCO_2}	3.114	3.206
C_{fCH_4}	0.00005	0.00005
C_{fN_2O}	0.00018	0.00018
TtW	77.46	75.08
WtW	94.26	92.78

Appendix 2
Barge Terminal Distances $D_{i,j}$.

Origin	Destination	Up/Down Stream	$D_{i,j}$
Barge Terminal Belém	Barge Terminal Manaus	U	1735
Barge Terminal Belém	Barge Terminal Porto Velho	U	2527
Barge Terminal Belém	Barge Terminal Santana	U	476
Barge Terminal Belém	Barge Terminal Santarém	U	1014
Barge Terminal Belém	Barge Terminal Vila do Conde	U	60
Barge Terminal Manaus	Barge Terminal Belém	D	1735
Barge Terminal Manaus	Barge Terminal Porto Velho	U	1239
Barge Terminal Manaus	Barge Terminal Santana	D	1259
Barge Terminal Manaus	Barge Terminal Santarém	D	721
Barge Terminal Manaus	Barge Terminal Vila do Conde	D	1774
Barge Terminal Porto Velho	Barge Terminal Belém	D	2527
Barge Terminal Porto Velho	Barge Terminal Manaus	D	1239
Barge Terminal Porto Velho	Barge Terminal Santana	D	2051
Barge Terminal Porto Velho	Barge Terminal Santarém	D	1513
Barge Terminal Porto Velho	Barge Terminal Vila do Conde	D	2566
Barge Terminal Santana	Barge Terminal Belém	D	476
Barge Terminal Santana	Barge Terminal Manaus	U	1259
Barge Terminal Santana	Barge Terminal Porto Velho	U	2051
Barge Terminal Santana	Barge Terminal Santarém	U	538
Barge Terminal Santana	Barge Terminal Vila do Conde	D	515
Barge Terminal Santarém	Barge Terminal Belém	D	1014
Barge Terminal Santarém	Barge Terminal Manaus	U	721
Barge Terminal Santarém	Barge Terminal Porto Velho	U	1513
Barge Terminal Santarém	Barge Terminal Santana	D	538
Barge Terminal Santarém	Barge Terminal Vila do Conde	D	1053
Barge Terminal Vila do Conde	Barge Terminal Belém	D	60
Barge Terminal Vila do Conde	Barge Terminal Manaus	U	1774
Barge Terminal Vila do Conde	Barge Terminal Porto Velho	U	2566
Barge Terminal Vila do Conde	Barge Terminal Santana	U	515
Barge Terminal Vila do Conde	Barge Terminal Santarém	U	1053
Barge Terminal Santa Clara	Barge Terminal Rio Grande	D	350
Barge Terminal Rio Grande	Barge Terminal Santa Clara	U	350

Source: Authors.

Appendix 3
Services Data.

	Cabotage Services																			
	AL ALCT 1 / LG SMN		**AL ALCT 2**		**AL ALCT 3 / LG SEA**		**AL ALCT 4 / LG SSR**		**AL ALCT 5**		**LG FSS**		**LG SSN**		**LG SAS / ML PLATA**		**ML BRACO**		**NC Amazonas**	
Terminals	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB
Porto Chibatão	**7**				**8**												**6**			
Super Terminais																			**5**	
Tecon Vila do Conde									**2**											
EMAP																				
APM Pecém	**6**	**8**	**5**		**7**				**1**						**8**		**5**		**4**	**6**
Tecon Suape	**5**	**9**	**4**		**6**										**7**		**4**	**7**	**3**	**7**
Tecon Salvador	**4**			**6**	**5**											**9**				
TVV							**5**													
Sepetiba Tecon	**3**																			
ICTSI Rio							**3**							**2**			**3**			
Multi Rio							**4**				**1**									
Tecon Santos	**1**			**7**	**2**		**1**												**1**	
BTP	**2**																			
DPW Santos					**1**		**2**								**6**	**10**	**1**			
TCP					**4**														**2**	
Porto Itapoá			**1**														**2**			

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Appendix 3 (*continued*)

	Cabotage Services																			
	AL ALCT 1 / LG SMN		**AL ALCT 2**		**AL ALCT 3 / LG SEA**		**AL ALCT 4 / LG SSR**		**AL ALCT 5**		**LG FSS**		**LG SSN**		**LG SAS / ML PLATA**		**ML BRACO**		**NC Amazonas**	
Terminals	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB
Portonave					**3**						**2**		**1**		**5**	**11**				
Tecon Imbituba			**3**																	
Tecon Rio Grande			**2**												**4**					
Montecon															**3**					
DPW Buenos Aires															**1**					
Tecplata															**2**					
Calls per Direction	**7**	**2**	**5**	**2**	**8**	**0**	**5**	**0**	**2**	**0**	**2**	**0**	**1**	**1**	**8**	**3**	**6**	**1**	**5**	**2**
Calls per Service	**9**		**7**		**8**		**5**		**2**		**2**		**2**		**11**		**7**		**7**	

Source: Authors – based on Cabotage Companies Published Schedules.
Numbers in the Terminals' lines represent the sequence of call at Terminals.
NB – North Bound Voyage
SB – South Bound Voyage

Appendix 4
Ships Data.

	Ships Names								
Aliança	Sebastião Caboto	Pedro Álvares Cabral	Fernão de Magalhães	Américo Vespúcio	Bartolomeu Dias	Vicente Pinzón	Maersk Ganges	Maersk Jalan	Aliança Leblon
Built Year	2013	2013	2013	2013	2014	2014	2014	2005	2005
Flag	Brasil	Brasil	Brasil	Brasil	Brasil	Brasil	Brasil	Brasil	Brasil
Callsign	PPOK	PPVG	PPYZ	PPSE	D5FT5	PPRP	PU8739	9 V3581	PPSV
IMO No.	9,602,875	9,603,219	9,603,221	9,603,233	9,625,384	9,625,396	9,694,581	9,294,161	9,292,137
DWT	51.668	51.668	52.072	51.668	57.882	57.881	65.223	39.383	23.299
GRT	42.564	42.564	42.564	42.564	47.799	47.799	51.872	28.592	18.334
Lenght (m)	228,00	228,00	228,00	228,00	254,70	254,70	255,00	222,14	175,00
Breadth (m)	37,30	37,30	37,30	37,30	37,30	37,30	37,30	30,00	27,40
Draught max. (m)	12,50	12,50	12,50	12,50	12,50	12,50	12,50	12,00	10,85
Nominal capacity (TEU)	3.868	3.884	3.765	3.765	4.800	4.800	5.400	2.826	1.740
Main Engine Buider	MAN B&W	MAN B&W	MAN B&W	MAN B&W	MAN B&W	MAN B&W	B&W	B&W	MAN B&W
Main Engine Model	7S70ME-C8	7S70ME-C8	7S70ME-C8	7S70ME-C8	8S70ME-C8	8S70ME-C8	6G50ME-B9.3	7K80MC-C	7S60MC-C
Total Power (kw)	22.890	19.456	19.456	19.456	22.236	22.236	27.680	25.270	14.206
Service	ALCT 1	ALCT 1	ALCT 1	ALCT 1	ALCT 2	ALCT 2	ALCT 2	ALCT 3	ALCT 5

Source: Authors – based on Cabotage Companies Published Schedules.

Appendix 4
Ships – continuation.

	Ships Names								
Log-In	Log-In Polaris	Log-In Jatobá	Log-In Discovery	Log-In Jacarandá	Log-In Endurance	Log-In Pantanal	Log-In Resiliente	Log-In Evolution	Log-In Experience
Built Year	2019	2009	2014	2011	2011	2007	2006	2024	2024
Flag	Brasil	Brasil	Brasil	Brasil	Brasil	Brasil	Brasil	Brasil	Brasil
Callsign	PU5668	PQ4801	5LAA7	PPSD	PU6073	PPVQ	PV3783	5LNR9	5LPY5
IMO No.	9,852,365	9,471,898	9,506,394	9,471,886	9,571,296	9,351,799	9,327,669	9,961,960	9,961,972
DWT	36.861	37.968	34.022	37.968	41.411	23.821	38.600	41.750	41.750
GRT	31.368	28.554	26.374	28.554	35.708	18.017	32.161	34.529	34.529
Lenght (m)	186,00	218,45	208,90	218,45	212,54	182,50	210,92	199,98	199,98
Breadth (m)	34,80	29,80	30,08	29,80	32,24	25,20	32,26	35,20	35,20
Draught max. (m)	11,00	11,60	11,60	11,60	12,50	10,00	12,00	11,00	11,00
Nominal capacity (TEU)	2.782	2.814	2.500	2.814	2.758	1.700	2.732	3.158	3.158
Main Engine Buider	MAN	Wartsila	MAN B&W	Wartsila	Wartsila	MAN B&W	MAN B&W	MAN-B&W	MAN-B&W
Main Engine Model	6G60ME-C	6RT-flex68	6K80ME-C	6RT-flex68	8RT-flex68	9 L58/64	7S70MC-C	6G60ME	6G60ME
Total Power KW	16.080	15.963	21.660	15.963	21.284	10.633	21.733	14.630	14.630
Service	SEA	SEA	SAS	SEA	SAS	SSR	SSV	SSN	SAS

(*continued on next page*)

Appendix 4 (*continued*)

	Ships Names								
Log-In	Log-In Polaris	Log-In Jatobá	Log-In Discovery	Log-In Jacarandá	Log-In Endurance	Log-In Pantanal	Log-In Resiliente	Log-In Evolution	Log-In Experience

	Ships Names				
Mercosul Line	Mercosul Santos	Mercosul Suape	Mercosul Itajaí	CMA CMG Veracruz	CMA CMG Santos
Built Year	2008	2008	2015	2010	2013
Flag	Brasil	Brasil	Brasil	Brasil	Brasil
Callsign	PPUT	PPUW	PPKQ	PU7643	PU7596
IMO No.	9,356,153	9,356,141	9,697,002	9,418,377	9,649,835
DWT	35.221	35.221	35.586	42.598	51.931
GRT	25.888	25.888	28.237	36.087	42.814
Lenght (m)	210,49	210,49	195,00	228,00	228,00
Breadth (m)	29,80	28,80	32,20	32,00	37,30
Draught max. (m)	11,40	11,14	11,50	12,00	12,80
Nominal capacity (TEU)	2.500	2.500	2.500	3.426	3.820
Main Engine Buider	MAN	MAN	MAN	Wartsila	MAN
Main Engine Model	7L70ME-C	7L70ME-C	6G60ME-C9.2	7RT-flex82C	7S70ME-C
Total Power KW	22.890	22.890	16.080	25.340	22.890
Service	BRACO	BRACO	BRACO	BRACO	PLATA

Source: Authors – based on Cabotage Companies Published Schedules.

Appendix 4

Ships Data – continuation.

Norcoast	NC Brisa	NC Bruma	NC Breda	NC Bravo
Built Year	2015	2015	2014	2015
Flag	Brasil	Brasil	Brasil	Brasil
Callsign	PU8163	PU8222	PU8237	PU8270
IMO No.	9,612,789	9,612,777	9,612,765	9,612,791
DWT	48.038	48.038	48.038	48.038
GRT	39.106	39.106	39.106	39.106
Lenght (m)	224,00	224,00	224,00	224,00
Breadth (m)	34,00	34,00	34,00	34,00
Draught max. (m)	12,0	12,0	12,0	12,0
Nominal capacity (TEU)	3.508	3.508	3.508	3.508
Main Engine Buider				
Main Engine Model				
Total Power KW				
Service	Amazonas	Amazonas	Amazonas	Amazonas

Appendix 5

ETA ($ETA_{s,i}$), ETB ($ETB_{s,i}$) and ETS ($ETS_{s,i}$) Dates.

Service	Port	BRSSZ	BRSSZ	BRIGI	BRSSA	BRSUA	BRPEC	BRMAO	BRPEC	BRSUA	BRSSZ
AL - ALCT 1	Terminal	Tecon Santos	BTP	Sepetiba Tecon	Tecon Salvador	Tecon Suape	APMT Pecém	Porto Chibatão	APMT Pecém	Tecon Suape	Tecon Santos
	ETA	08/30/2024 13:00	09/01/2024 00:00	09/02/2024 06:00	09/05/2024 04:00	09/07/2024 05:00	09/09/2024 06:00	09/14/2024 12:00	09/21/2024 15:00	09/23/2024 07:00	09/27/2024 13:00
	ETB	08/30/2024 13:00	09/01/2024 00:00	09/02/2024 06:00	09/05/2024 04:00	09/07/2024 05:00	09/09/2024 06:00	09/14/2024 12:00	09/21/2024 15:00	09/23/2024 07:00	09/27/2024 13:00
	ETS	08/31/2024 19:00	09/01/2024 18:00	09/02/2024 18:00	09/05/2024 19:00	09/07/2024 21:00	09/09/2024 19:00	09/17/2024 16:00	09/22/2024 02:00	09/23/2024 19:00	09/28/2024 19:00

Service	Port	BRSSZ	BRIOA	BRRIG	BRIBI	BRSUA	BRPEC	BRSSA	BRSSZ
AL - ALCT 2	Terminal	Tecon Santos	Porto Itapoá	Tecon Rio Grande	Tecon Imbituba	Tecon Suape	APMT Pecém	Tecon Salvador	Tecon Santos
	ETA	09/26/2024 01:00	09/27/2024 13:00	09/29/2024 17:00	10/02/2024 07:00	10/08/2024 09:00	10/10/2024 10:00	10/13/2024 14:00	10/17/2024 01:00
	ETB	09/26/2024 01:00	09/27/2024 13:00	09/29/2024 17:00	10/02/2024 07:00	10/08/2024 09:00	10/10/2024 10:00	10/13/2024 14:00	10/17/2024 01:00
	ETS	09/26/2024 19:00	09/28/2024 07:00	09/30/2024 12:00	10/04/2024 03:00	10/09/2024 05:00	10/11/2024 09:00	10/14/2024 07:00	10/17/2024 19:00

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Appendix 5 (*continued*)

Service	Port	BRSSZ	BRIOA	BRRIG	BRIBI	BRSUA	BRPEC	BRSSA	BRSSZ

Service	Port	BRSSZ	BRNVT	BRSSA	BRSUA	BRPEC	BRMAO	BRSSZ
AL - ALCT 3 LG - SEA	Terminal	Tecon Santos	Portonave	Tecon Salvador	Tecon Suape	APMT Pecém	Porto Chibatão	Tecon Santos
	ETA	09/01/2024 15:00	09/04/2024 01:00	09/07/2024 17:00	09/09/2024 20:00	09/12/2024 01:00	09/17/2024 13:00	29/09/2024 15:00
	ETB	09/01/2024 15:00	09/04/2024 01:00	09/07/2024 17:00	09/09/2024 20:00	09/12/2024 01:00	09/17/2024 13:00	29/09/2024 15:00
	ETS	09/02/2024 11:00	09/04/2024 12:00	09/08/2024 01:00	09/10/2024 08:00	09/12/2024 10:00	09/19/2024 15:00	30/09/2024 11:00

Service	Port	BRSSZ	BRRIO	BRRIO	BRVIX	BRSSZ
AL - ALCT 4 LG - SSR	Terminal	Tecon Santos	ICTSI Rio	Multi Rio	TVV	Tecon Santos
	ETA	10/09/2024 19:00	10/11/2024 06:00	10/11/2024 17:00	10/13/2024 03:00	10/16/2024 19:00
	ETB	10/09/2024 19:00	10/11/2024 06:00	10/11/2024 17:00	10/13/2024 03:00	10/16/2024 19:00
	ETS	10/10/2024 11:00	10/11/2024 14:00	10/11/2024 23:00	10/14/2024 13:00	10/17/2024 11:00

Source: Authors – based on Cabotage Companies Published Schedules.

Appendix 5
ETA ($ETA_{s,i}$), ETB ($ETB_{s,i}$) and ETS ($ETS_{s,i}$) Dates – continuation.

Service	Port	BRPEC	BRVLC	BRPEC
AL - ALCT 5	Terminal	APMT Pecém	Tecon Vila do Conde	APMT Pecém
	ETA	09/18/2024 01:00	09/21/2024 01:00	09/25/2024 01:00
	ETB	09/18/2024 01:00	09/21/2024 01:00	09/25/2024 01:00
	ETS	09/19/2024 00:01	09/23/2024 01:00	09/26/2024 00:01

Service	Port	BRRIO	BRVIX	BRRIO
	Terminal	Multi Rio	TVV	Multi Rio
	ETA	09/29/2024 23:00	10/02/2024 09:00	10/06/2024 23:00
	ETB	09/30/2024 01:00	10/02/2024 11:00	10/07/2024 01:00
	ETS	10/01/2024 01:00	10/05/2024 11:00	10/08/2024 01:00

Service	Port	BRRIO	BRNVT	BRIGI	BRRIO
LG - SSN	Terminal	Multi Rio	Portonave	Sepetiba Tecon	Multi Rio
	ETA	10/01/2024 17:00	10/04/2024 19:00	10/07/2024 20:00	10/08/2024 17:00
	ETB	10/01/2024 19:00	10/04/2024 20:00	10/07/2024 23:00	10/08/2024 19:00
	ETS	10/03/2024 19:00	10/05/2024 20:00	10/08/2024 07:00	10/10/2024 19:00

Service	Port	ARBUE	UYMVD	BRRIG	BRNVT	BRSSZ	BRSUA	BRPEC	BRSSA	BRSSZ	BRNVT	ARBUE
LG - SAS ML - Plata	Terminal	DPW Buenos Aires	Montecon	Tecon Rio Grande	Portonave	DP World Santos	Tecon Suape	APMT Pecém	Tecon Salvador	DP World Santos	Portonave	DPW Buenos Aires
	ETA	09/08/2024 11:00	09/10/2024 18:00	09/12/2024 22:00	09/15/2024 12:00	09/17/2024 00:01	09/21/2024 18:00	09/24/2024 06:00	09/27/2024 11:00	10/01/2024 11:00	10/03/2024 07:00	06/10/2024 11:00
	ETB	09/08/2024 23:00	09/10/2024 19:00	09/12/2024 23:00	09/15/2024 13:00	09/17/2024 01:00	09/21/2024 19:00	09/24/2024 07:00	09/27/2024 12:00	10/01/2024 13:00	10/03/2024 09:00	06/10/2024 23:00
	ETS	09/10/2024 05:00	09/11/2024 06:00	09/13/2024 23:00	09/16/2024 06:00	09/17/2024 17:00	09/22/2024 21:00	09/24/2024 22:00	09/28/2024 02:00	10/02/2024 03:00	10/03/2024 21:00	08/10/2024 05:00

Source: Authors – based on Cabotage Company Published Schedules.

Appendix 5
ETA ($ETA_{s,i}$), ETB ($ETB_{s,i}$) and ETS ($ETS_{s,i}$) Dates – continuation.

Service	Port	BRSSZ	BRIOA	BRRIO	BRSUA	BRPEC	BRMAO	BRSUA	BRSSZ
ML - Braco	Terminal	DP World Santos	Porto Itapoá	ICTSI Rio	Tecon Suape	APMT Pecém	Porto Chibatão	Tecon Suape	DP World Santos
	ETA	10/02/2024 06:00	10/04/2024 06:00	10/06/2024 06:00	10/10/2024 02:00	10/12/2024 06:00	10/17/2024 19:00	10/25/2024 19:00	10/30/2024 06:00

(*continued on next page*)

Appendix 5 (*continued*)

Service	Port	BRSSZ	BRIOA	BRRIO	BRSUA	BRPEC	BRMAO	BRSUA	BRSSZ
	ETB	10/02/2024 06:00	10/04/2024 06:00	10/06/2024 06:00	10/10/2024 02:00	10/12/2024 06:00	10/17/2024 19:00	10/25/2024 19:00	10/30/2024 06:00
	ETS	10/03/2024 08:00	10/04/2024 20:00	10/06/2024 16:00	10/10/2024 17:00	10/12/2024 14:00	10/19/2024 23:00	10/26/2024 09:00	10/31/2024 08:00

Service	Port	BRSSZ	BRPNG	BRSUA	BRPEC	BRMAO	BRPEC	BRSUA	BRSSZ
NC - Amazonas	Terminal	Tecon Santos	TCP	Tecon Suape	APMT Pecém	Super Terminais	APMT Pecém	Tecon Suape	Tecon Santos
	ETA	06/09/2024 12:00	07/09/2024 13:00	12/09/2024 05:00	14/09/2024 04:00	19/09/2024 15:00	25/09/2024 04:00	27/09/2024 05:00	04/10/2024 12:00
	ETB	06/09/2024 13:00	07/09/2024 14:00	12/09/2024 06:00	14/09/2024 06:00	19/09/2024 16:00	25/09/2024 06:00	27/09/2024 06:00	04/10/2024 13:00
	ETS	07/09/2024 01:00	08/09/2024 06:00	12/09/2024 18:00	14/09/2024 18:00	21/09/2024 11:00	25/09/2024 11:00	27/09/2024 12:00	05/10/2024 01:00

Source: Authors – based on Cabotage Companies Published Schedules.

Appendix 6
Port Distance in Nautical Miles ($D_{i,i+1}$),

	Port Distances (nm)															
Port	BRMAO	BRVLC	BRITQ	BRPEC	BRSUA	BRSSA	BRVIX	BRIGI	BRRIO	BRSSZ	BRPNG	BRIOA	BRITJ	BRNVT	BRIBI	BRRIG
BRMAO	0	873	1.300	1.569	2.046	2.409	2.832	3.170	3.102	3.300	3.430	3.460	3.469	3.469	3.538	3.835
BRVLC	873	0	427	696	1.173	1.536	1.959	2.297	2.229	2.427	2.557	2.587	2.596	2.596	2.665	2.962
BRITQ	1.300	427	0	381	837	1.212	1.635	1.973	1.905	2.103	2.233	2.263	2.272	2.272	2.341	2.638
BRPEC	1.569	696	381	0	478	853	1.276	1.614	1.546	1.744	1.874	1.876	1.913	1.913	1.982	2.282
BRSUA	2.046	1.173	837	478	0	375	798	1.129	1.061	1.259	1.389	1.419	1.428	1.428	1.497	1.844
BRSSA	2.409	1.536	1.212	853	375	0	482	813	745	943	1.073	1.103	1.112	1.112	1.181	1.478
BRVIX	2.832	1.959	1.635	1.276	798	482	0	350	282	480	610	640	649	649	718	1.015
BRIGI	3.170	2.297	1.973	1.614	1.129	813	350	0	68	191	322	350	366	366	433	738
BRRIO	3.102	2.229	1.905	1.546	1.061	745	282	68	0	220	350	380	389	389	458	755
BRSSZ	3.300	2.427	2.103	1.744	1.259	943	480	191	220	0	168	192	226	226	286	606
BRPNG	3.430	2.557	2.233	1.874	1.389	1.073	610	322	350	168	0	60	104	104	181	499
BRIOA	3.460	2.587	2.263	1.876	1.419	1.103	640	350	380	192	60	0	63	63	143	461
BRITJ	3.469	2.596	2.272	1.913	1.428	1.112	649	366	389	226	104	63	0	1	93	411
BRNVT	3.469	2.596	2.272	1.913	1.428	1.112	649	366	389	226	104	63	1	0	93	411
BRIBI	3.538	2.665	2.341	1.982	1.497	1.181	718	433	458	286	181	143	93	93	0	322
BRRIG	3.835	2.962	2.638	2.282	1.844	1.478	1.015	738	755	606	499	461	411	411	322	0

Source: Authors based on ANTAQ data.

Appendix 7
Port Call Cost ($S_{s,i}^{PC}$).

Port Call Cost (USD) per Vessel Class							
Port Name	Port	4500 TEU	4000 TEU	3500 TEU	3000 TEU	2500 TEU	2000 TEU
Manaus	BRMAO	387.200	352.000	320.000	288.000	273.600	246.240
Vila do Conde	BRVLC	16.940	15.400	14.000	12.600	11.970	10.773
Itaqui	BRITQ	20.570	18.700	17.000	15.300	14.535	13.082
Pecém	BRPEC	29.040	26.400	24.000	21.600	20.520	18.468
Suape	BRSUA	19.360	17.600	16.000	14.400	13.680	12.312
Salvador	BRSSA	18.150	16.500	15.000	13.500	12.825	11.543
Vitória	BRVIX	16.940	15.400	14.000	12.600	11.970	10.773
Itaguaí	BRIGI	21.780	19.800	18.000	16.200	15.390	13.851
Rio de janeiro	BRRIO	21.780	19.800	18.000	16.200	15.390	13.851
Santos	BRSSZ	45.980	41.800	38.000	34.200	32.490	29.241
Paranaguá	BRPNG	26.620	24.200	22.000	19.800	18.810	16.929
Itapoá	BRIOA	22.990	20.900	19.000	17.100	16.245	14.621
Itajaí	BRITJ	22.990	20.900	19.000	17.100	16.245	14.621
Navegantes	BRNVT	22.990	20.900	19.000	17.100	16.245	14.621
Imbituba	BRIBI	22.990	20.900	19.000	17.100	16.245	14.621
Rio Grande	BRRIG	26.620	24.200	22.000	19.800	18.810	16.929

Source: Authors, based on information from a Cabotage company.

Appendix 8
Ships Class Daily Cost (S_s^{DC}).

Vessel Daily Cost per Class (S_S^{DC})								
Class	5.000	4.500	4.000	3.500	3.000	2.500	2.000	Unity
Daily Cost including P&I	20.000	18.000	16.000	14.000	12.000	10.000	8.000	USD/day

Source: Authors, based on information from a Cabotage company.

Appendix 9
Terminal Handling Charges (THC_i *and* THC_j).

Brazilian Terminal Handling Charges - THC		
Port Code	Port Name	THC (BRL/container)
BRIBI	Imbituba	860
BRIGI	Itaguaí	676
BRIOA	Itapoá	783
BRITJ	Itajaí	886
BRMAO	Manaus	868
BRNVT	Navegantes	875
BRPEC	Pecém	894
BRPNG	Paranaguá	1.180
BRRIG	Rio Grande	1.107
BRRIO	Rio de Janeiro	623
BRSLZ	São Luís	970
BRSSA	Salvador	1.213
BRSSZ	Santos	1.164
BRSUA	Suape	1.457
BRVIX	Vitória	1.276
BRVLC	Vila do Conde	962
Average		987

Source: Authors, based on web search.
THC average values were obtained on the WEB accessing the following Deep Sea Shipping Companies links in April 2024.
Maersk: https://www.maersk.com/news/articles/2023/06/02/terminal-handling-service-ohc-dhc-brazil-world.
CMA CGM: https://www.cma-cgm.com/static/BR/Attachments/BRAZIL%20-%20LOCAL%20SCES%20Jul%2023.pdf.
ONE: https://br.one-line.com/sites/g/files/lnzjqr1461/files/2023-10/LOCAL%20SURCHARGES%20-%20BR%20-%20%20V26.pdf.
Hapag Lloyd: https://www.hapag-lloyd.com/content/dam/website/downloads/pdf/Global_Mastertemplate_THC_LBR_as_from_April_1_2023.pdf.
COSCO: https://coscoshipping.com.br/wp-content/uploads/2023/09/Brazil-Local-Charges-Change-from-CNR-to-CHC-code-name-Efferctive-from-Sep-24-2023-Updated-by-HQ-Aug-24-2023_.pdf.

Appendix B. Appendix 10. Sensitivity Analysis Equations.

$$D_{i,j} = 0,90\ D_R^C \frac{A}{B}$$

$$A = \left(\frac{2Tcd}{(1-M_R)} + \frac{vi}{d} + F_c^D F_e^D \frac{F_f^D}{1000000} Cp \right) + \frac{Tcc}{(1-M_R)} + \frac{1}{(1-M_c)} (2\ SLOT_S + THC_o + THC_d) + TT_S (vi + 2\ EF_S\ Cp)$$

$$B = \left(\frac{Tcd}{1-M_R} + \frac{vi}{d} + F_c^D F_e^D \frac{F_f^D}{1000000} Cp \right)$$

Where,
$D_{i,j}$ = Road distance between origin and destination cities
D_R^C = Sum of the distance between origin city and port of loading and port of discharge and destination city
TT_S = Service transit time
THC_o = Port of Loading Terminal Handling Charge
THC_d = Port of Discharge Terminal Handling Charge
All other parameters as per Eqs. 1 and 9.

Appendix 11
Sensitivity Analysis Parameters per Scenario.

Road										
Parameter	Unit	Scenario Base	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
$D_{i,j}$	km	various	various	various	various	various	various	various	various	various
T_{CD}	BRL/km	60,684	60,684	60,684	60,684	60,684	60,684	60,684	60,684	60,684
T_{CC}	BRL/km	518,35	518,35	518,35	518,35	518,35	518,35	518,35	518,35	518,35
d	km/day	715	715	715	715	715	715	715	715	715
M_R	%	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15
v	BRL	200.000	200,000	200,000	200,000	500,000	200,000	200,000	200,000	200,000
i	%/day	0,0005	0,0005	0,0005	0,0005	0,0005	0,001	0,0005	0,0005	0,0005
F_c^D	liters/km	0,28	0,28	0,28	0,28	0,28	0,28	0,28	0,28	0,28
F_e^D	MJ/l	35,52	35,52	35,52	35,52	35,52	35,52	35,52	35,52	35,52
F_f^D	gCO_2eq/MJ	86,5	86,5	17,3	86,5	86,5	86,5	86,5	86,5	86,5
Cp	BRL/tCO_2e	356,2	356,2	356,2	356,2	356,2	356,2	100	356,2	356,2

Cabotage										
Parameter	Unit	Scenario Base	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
2 SLOT	BRL	5397	4317,6	5397	5397	5397	5397	5397	5397	6476,4
Transit Time	day	10,5	10,5	10,5	10,5	10,5	10,5	10,5	16	10,5
$2\ EF_S$	gCO_2eq/day	0,12	0,12	0,12	0,024	0,12	0,12	0,12	0,12	0,12
THC_i	BRL	988	988	988	988	988	988	988	988	1185,6
THC_j	BRL	988	988	988	988	988	988	988	988	1185,6
M_C	%	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15
v	BRL	200.000	200,000	200,000	200,000	500,000	200,000	200,000	200,000	200,000
i	%/day	0,0005	0,0005	0,0005	0,0005	0,0005	0,001	0,0005	0,0005	0,001
Cp	BRL/tCO_2eq	356,2	356,2	356,2	356,2	356,2	356,2	100	356,2	356,2

Source: Authors.

Data availability

Data will be made available on request.

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