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Chasing Optimization on Multimodal Transportation System: A Strategic Approach to Minimizing Costs and CO2 Emissions

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Abstract: This study aims to enhance multimodal transportation systems by mitigating CO2 emissions and enhancing operational efficiency. It introduces a novel centralized cargo concentration approach tailored for regions facing geographical challenges. The method proposes for direct transportation of cargo from its loading origin to export ports, bypassing intermediate hubs. The mathematical model determines the most efficient means of transport for each route, factoring in variables like distance, volume, and cargo type. Research results indicate that, in scenarios with a high concentration of cargo, multiple hubs may not be necessary, which could streamline transportation and logistics operations. Modal preferences vary based on regional dynamics and cargo characteristics, with rail and sea transport emerging as preferable options under specific circumstances, surpassing the efficacy of road transport. The proposed model showcases reductions in both logistics costs and CO2 emissions compared to road-centric scenarios. It underscores the strategic integration of diverse transportation modes as pivotal for enhancing efficiency and sustainability. This study furnishes a framework adaptable to optimizing multimodal transportation systems in regions sharing similar geographical and logistical attributes.

Keywords: hub and spoke; national logistic; multimodal system; emissions reduction

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1. Introduction

Addressing emissions in the transportation sector stands as an essential, with optimizing its structure emerging as a pivotal strategy toward. According to the International Energy Agency, in 2018, emissions from transportation constituted a 25% of global emissions [1]. Without effective interventions, projections suggest this figure could escalate to 30% by 2030 and 50% by 2050 [2]. Notably, despite road transport representing over 70% of total transportation, its carbon intensity exceeds that of rail transport by fourfold and that of inland waterway transport by tenfold [2].

In the domain of multimodal port transportation, the strategic placement of hubs emerges as a critical factor for cargo consolidation, thereby optimizing both time and operating costs and contributing significantly to the reduction of CO2 emissions. This approach not only fortifies linkages between importing/exporting entities and port terminals, thereby bolstering their competitiveness and customer satisfaction[3], but also plays a pivotal role in crafting efficient supply chain networks and multimodal transportation systems. These networks, modeled on a hub-and-spoke paradigm, centralize operations and facilitate transshipment, consolidation, and sorting of cargo [4], achieving economies of scale and optimizing variable transportation costs. Such optimization improves shipping capabilities concerning weight, volume, accessibility, and transit times [5]. Moreover, this structured

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approach fosters cargo mobility, slashes greenhouse gas emissions, and augments efficiency in long-haul transportation, amplifying the advantages of local transportation [5–7].

The embrace of multimodal transportation hinges on several factors, including geographical attributes, allocation of public funds, and effective coordination among ports. This decision necessitates a comprehensive evaluation of the pros and cons inherent in each transportation mode[8]. Despite entailing substantial upfront investments, the multimodal system stands out for its operational efficiency and reduced environmental impact, outstripping the advantages of solely land-based transportation. This preference is substantiated by its capability to curtail greenhouse gas emissions and preserve road infrastructure, due to the alleviated burden on truck traffic [9].

The allocation and distribution of cargo in mathematical models have been widely studied in the literature. These models encompass location and routing schemes crucial for optimizing transport in multimodal ports. Notably, the Vehicle Routing Problem (VRP) and its variants, such as the Capacitated Vehicle Routing Problem (CVRP), have been extensively studied [10].The CVRP involves a fleet of homogeneous vehicles with limited capacity, while an extension, the Vehicle Routing Problem with Time Windows (VRPTW), focuses on deliveries within predefined time windows[11]. Unlike the Traveling Salesman Problem (TSP), where a single vehicle visits all points in the network, in the VRP, each vehicle serves a specific subset of points, adding complexity to the problem[12]. The VRP is a common application in distributing goods and end products from factories to multiple customers, utilizing a fleet of vehicles without intermediate storage[13]. However, integrating intermediate warehouses into logistics network design, known as the Capacitated Locations Routing Problem (CLRP), can significantly enhance efficiency[14]. The CLRP, combining the Facility Location Problem (FLP) with the VRP[15], presents a complex logistical challenge in supply chain management, involving the selection of distribution centers, customer assignment, and determining optimal delivery sequences to minimize total costs, including distribution and depot location[16].

In the field of route optimization in port contexts, various methods have been deployed to enhance operational efficiency. Deep reinforcement learning has been utilized to minimize empty truck trips, while genetic algorithms and greedy-type heuristics have aided in reducing bottlenecks and pollutant emissions[17,18]. Additionally, the amalgamation of Monte Carlo simulation with linear programming has proven effective in curtailing carbon footprint[19,20].

1.1. Contribucion

In this paper, a new approach called "multimodal approach under central freight concentration" is introduced, which redefines and customizes traditional multimodal transportation strategies. This model, based on [13], is applied in the unique geographical context of Chile, a country with a longitudinal length of 4,270 km and a width variation between 445 and 90 km.

The significance of this model arises from the pronounced concentration of cargo within the central zone of Chile, encompassing the capital and its proximate regions within a 120 km radius. Conventional hub model or concentration nodes, as per [21], prove ineffective given this geographical layout. Consequently, an alternative is proposed that advocates direct transport of cargo from its origin to the ports of export, effectively bypassing the need for intermediate hubs.

The main contribution of this research is that, in scenarios where a high concentration of cargo is observed in a specific node, it is not essential to implement multiple hubs for cargo concentration, which could significantly optimize the transportation and logistics process.

1.2. Motivation

In the global context, the importance of multimodal transportation is emphasized by a study conducted by the European Union, projecting a potential reduction of up to 40% in greenhouse gas emissions by 2030 compared to 1990 [22].

Additionally, [8] underscores the significance of multimodal transportation, delineating its three integral segments: collection, main transportation, and distribution within logistics frameworks.

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Concurrently, [23] delves into the intricacies of the agricultural logistics chain in China, revealing that road congestion contributes to a carbon emission surge of over 20%, thus advocating for route optimization for cold chain containers to mitigate such adverse impacts.

The present study centers on optimizing transportation routes within Chilean ports, aligning with strategic objectives outlined by the Chilean government. This strategic approach aims to strengthen national export and import logistics chains by 2030, highlighting the necessity of adapting to global sustainability trends while tackling existing challenges within freight transportation. Notably, in 2021, logistics costs in Chile constituted 18% of GDP, a figure markedly higher than the OECD average of 9% [24].In response to this scenario, the Chilean government's Budget Directorate has been promoting innovation in research and development to enhance the country's productivity, competitiveness, and diversification of production [25]. Furthermore, the Chilean Economic Development Agency identified deficiencies in the intermodal network as early as 2017, thereby driving initiatives aimed at fostering smarter port infrastructure development [26].

The aim is to answer key questions:

- How to optimize the route in a freight transport network with limitations of port and multimodal transport?
- How to improve the efficiency of truck routes in ports to reduce CO2 emissions and transportation times?
- What is the optimal geographical location for a container consolidation center in a port network?

This study provides a methodological framework to answer the research questions posed, focusing on the adaptation of existing transportation models to the particularities and specific needs of Chile.

This research is structured into several sections: Section 1 introduces the context, contribution, and motivation of the study. Section 2 covers the theoretical background, providing a description of the transportation network in Chile and an exhaustive literature review. Section 3 details the materials and methods used. Section 4 is dedicated to the practical application development of the study. Finally, Sections 5 and 6 present the results, discuss the findings, and provide the conclusions of the research.

2. Background

2.1. Description of System

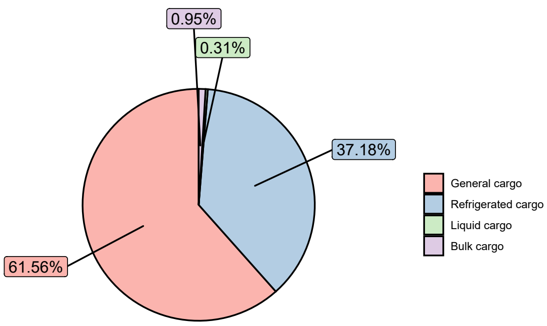
Chile's transportation network is a linchpin of its open economy, constituting 11.7% of GDP in 2022, encompassing roads, railways, and coastal shipping. In 2023, cargo distribution comprised solid bulk (47%), liquid bulk (22%), general cargo containers (24%), refrigerated cargo (4.4%), and other types (2.6%) CAMPORT2024. These goods traverse a comprehensive network of land, rail, and maritime infrastructure to reach public and private ports, which collectively manage 96.4% of the country's imports and exports CAMPORT2024. Despite its pivotal role, multimodal transportation remains underdeveloped compared to individual modes.

Chile boasts 3,570 kilometers of paved dual-carriageway roads and a total road network spanning 28,700 kilometers, with 15,441 kilometers being asphalted [27]. Additionally, its national road infrastructure extends to 88,510 kilometers [27]. The railway infrastructure, predominantly linking central zones with maritime ports, plays a pivotal role in facilitating the transportation of a wide array of cargo.

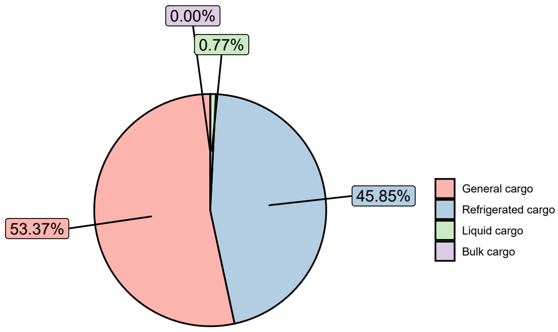
Regarding port infrastructure, Chile harbors 56 ports, comprising 10 state-owned public ports, 14 privately-owned public ports, and 32 private ports. Among them, the ports of Valparaíso, featuring 8 docking sites across 5 docks, and San Antonio, with 3 docks and 8 docking sites, hold prominence in this study [28]. Seven out of the ten state-owned port companies operate under active concession contracts [29].

The country's domestic transportation primarily relies on road, rail, and coastal shipping, with 88% of tonnage destined for international trade and 12% for the domestic market [30]. Containerized cargo is distributed as follows: 42.7% in imports, 45.1% in exports, 8.6% in transit, and 3.4% in coastal shipping, mobilizing 12% of domestic trade in containers [31]. Major cargo types include solid waste, cellulose, copper concentrate, general cargo containers, metallic copper, and agricultural products, among others, transported from production and distribution centers to port facilities.

In Figures 1.a and 1.b, the percentages by type of cargo for the ports of San Antonio and Valparaíso are shown.



(a) San Antonio Port



(b) Valparaíso Port

Figure 1. Types of cargo from origin to port.

2.2. Related Works

To understand how to model routes in freight transport networks considering port and multimodal limitations, optimize the location of distribution centers with a space-time approach, and comprehend the challenges and decisions related to reducing pollutant emissions and logistic inefficiencies, an exhaustive literature review was conducted using the Web of Science and SCOPUS databases. The query used was: (TS=(("Freight transport" or "Logistics planning" or "Route optimization" or "Freight consolidation") and ("Multimodal" or "transport optimization" or "Transport network") and ("port")). The resulting research from the search was qualitatively analyzed, selecting those presented in Table 1.

Table 1. Limitations and Contributions of Multimodal Transport Networks

Author	Method/ model/ technique	Limitations	Contributions
Transport industry:			
[5]	Multi-objective planning model	Exploring model applicability in various regions, incorporating diverse transport modes, and managing dynamic supply chain and logistics uncertainties are essential areas for research.	Rail transport is the most efficient mode for long distances, surpassing other methods in cost and carbon emissions.
[32]	Mathematical modeling to design service schedules for synchromodal freight transport systems.	Examines a case of the Port of Rotterdam hinterland network, limiting generalizability. The study lacks information on barriers to synchromodal freight transport systems.	Improved performance of the intermodal freight system, achieving cost savings, equivalent to a reduction of more than 20%.
[33]	SynchroMO algorithm	The study of the hinterland network of the Port of Rotterdam could limit the relevance of the results. Analysis is required for infrastructure, stakeholder collaboration, and regulations.	It allows simulations and comparisons to be made between different routes and schedules, depending on the goods transiting the Rotterdam hinterland container transport.
[34]	Genetic algorithm	The study examines 10 regional capitals in Ghana, limiting generalizability. The genetic algorithm model considers time, distance, and CO2 emissions, but overlooks other sustainability factors.	By optimizing the system, total cost savings were achieved, representing a reduction of 4.5 % compared to the same amount of cargo transported with the traditional system.
[35]	ArcGIS and event model	The research centers on GIS modeling of freight transportation and logistics in Russia. It does not mention the specific event model employed or the constraints of the GIS model. The absence of exploration into potential biases of the data utilized.	Optimizes the planning and coordination of the transportation and logistics system in the city of St. Petersburg, thus improving regional connectivity within Europe.
[36]	Stochastic integer programming model	The paper presents an optimization model for load allocation in synchromodal transport, but lacks detailed information on solution techniques, focuses on a specific problem and lacks assumptions in the model.	Improves sustainability, increases flexibility and reduces costs, among other benefits, in the field of freight transportation.
[37]	Multi-objective optimization and genetic algorithm	The investigation focuses on transportation cost, fixed cost, and CO2 emissions while overlooking factors such as social impacts, land use, and noise pollution. Challenges and limitations in applying the model for real-world decisions are not analyzed.	Inland ports are positioned in a multimodal freight transport network to optimize transport and operational costs while lowering CO2 emissions. The growth of inland ports is linked to cost and emission reductions.
[38]	Multimodal environment evaluation tool (MEET)	The study examines how modal shifts in Shenzhen affect air quality, without considering social impacts, land use changes, or noise pollution. More research is required to assess the success of accompanying strategies and measure extra advantages.	Replacing road transport with sustainable options such as rail and river transport can benefit port cities in terms of transport efficiency and environmental quality. Stricter emission standards for vehicles can improve air quality by reducing NOX and O3 levels.
[39]	Data envelopment analysis (DEA) model	The research explores carbon emissions efficiency of rail-water intermodal transport in China, but findings may not be generalizable. It concentrates on CO2 emissions and overlooks other environmental impacts or pollutants.	Evaluates the carbon emission efficiency of rail-water intermodal transport in 14 Chinese ports, facilitating sustainable transport planning and decision making.
[40]	Multi-objective optimization	The research on a European port freight transport network may limit generalizability. Other factors like infrastructural constraints and regulatory policies could affect CO2 emissions and logistics costs balance.	Examines the relationship between logistics costs and CO2 emissions in various freight transport networks. Evaluates the effects of changing modes and routes on the balance between costs and emissions, emphasizing the role of the demands and capacities of the freight transport system.
[41]	Integrates Dijkstra's algorithm and a pattern search algorithm in a bi-level programming model	It is necessary to examine the risks of implementing the subsidy mechanism in the various modes of transport and logistics planning. Further analysis is required to understand the economic, social, environmental and political effects of the proposal.	Utilizes Yangtze River data to optimize China Railway Express freight subsidy system in multimodal transport setup, improving decision-making and policy development for sustainable transport. Sets specific intervals for adjusting unit subsidy based on type of cargo being transported.

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Table 1. *Cont.*

Author	Method/ model/ technique	Limitations	Contributions
Industria Portuaria [42]	Linear optimization	An in-depth examination is needed on transport strategies, associated risks, and subsidy mechanisms implications. Real-world uncertainties like personnel performance in port operations and current regulations must be evaluated.	Examines carbon reduction methods in supply chains of London Gateway, studying alternative ports and transport modes like short sea shipping. Decreasing travel distances and CO2e emissions leads to lower costs.
[43]	Logistic regression model	The logistic regression model of the case study needs to study service reliability and environmental impact to improve the effectiveness of the service design.	Optimizing SSS services in intermodal transport chains involves designing the optimal vessel size based on demand estimation. A case study of a Ro-Pax service in Portugal shows how design adjustments can improve economic performance.
[44]	Stochastic network assignment model and global logistics intermodal network simulation model	The model neglects external factors like politics or economics affecting logistics flow. Simulation results are restricted by data availability and accuracy for comparison with observed flows.	Evaluates logistics infrastructure policies in the Greater Mekong subregion of Myanmar, tests various scenarios to determine their effects on goods movement and container traffic. Analyzes the environmental and economic impact of increased truck speed and the opening of the Dawei port on transport modes.
[45]	Two-stage stochastic mixed integer model (MIP)	Lack of consideration of weather conditions, port congestion and labor availability, which affects throughput and operating costs. More accurate costing is required for various scenarios and terminals.	Examine how uncertainty affects barge transportation by analyzing real data from a land terminal and evaluating long-term performance through simulated weekly operations for one year. Creates a stochastic program for transportation planning that demonstrates that uncertainty can influence total costs.
[46]	Interport Model (network programming tool)	The model examines the rationality of economic agents and perfect competition. It is convenient to study the uncertainty of factors such as container demand, costs, capacity constraints and regulatory changes.	Investigate the link between sustainability and container logistics in Campania ports. Examine the impact of policies and measures on the competitiveness and sustainability of container distribution. Emphasizes the reduction of transport costs and suggests public and private strategies for green transport.

Table 1 illustrates the main applications of multimodal transportation in the transportation and port industry, revealing a variety of employed mathematical models. However, these models focus on specific aspects and do not address the vehicle routing problem, such as the Vehicle Routing Problem (VRP), its variants like the Capacitated Vehicle Routing Problem (CVRP) [10], or the hub and spoke model, utilized in this study [13,21].

Unlike these methodologies that tackle specific aspects of the problem, this article proposes a comprehensive model for the operation of the entire system. The objective is to minimize the total cost and reduce the ton-kilometers transported, thus contributing to the decrease in pollutant emissions.

3. Optimization Modeling

3.1. Model Assumptions

In this study, classical optimization was employed due to its ability to generate interpretable and transparent solutions, which is suitable in scenarios with limited data where machine learning methods are not applicable due to the lack of high-quality data. Classical optimization, efficient due to its simplicity and lower demand for computational resources, proves to be particularly effective compared to techniques such as deep learning in contexts with clear deterministic rules, providing analytical solutions without the need for large volumes of information.

A mathematical model is used to determine the distribution of loads and warehouses, identifying concentration and distribution nodes, as shown in the conceptual diagram of the multimodal system in Figure 2.

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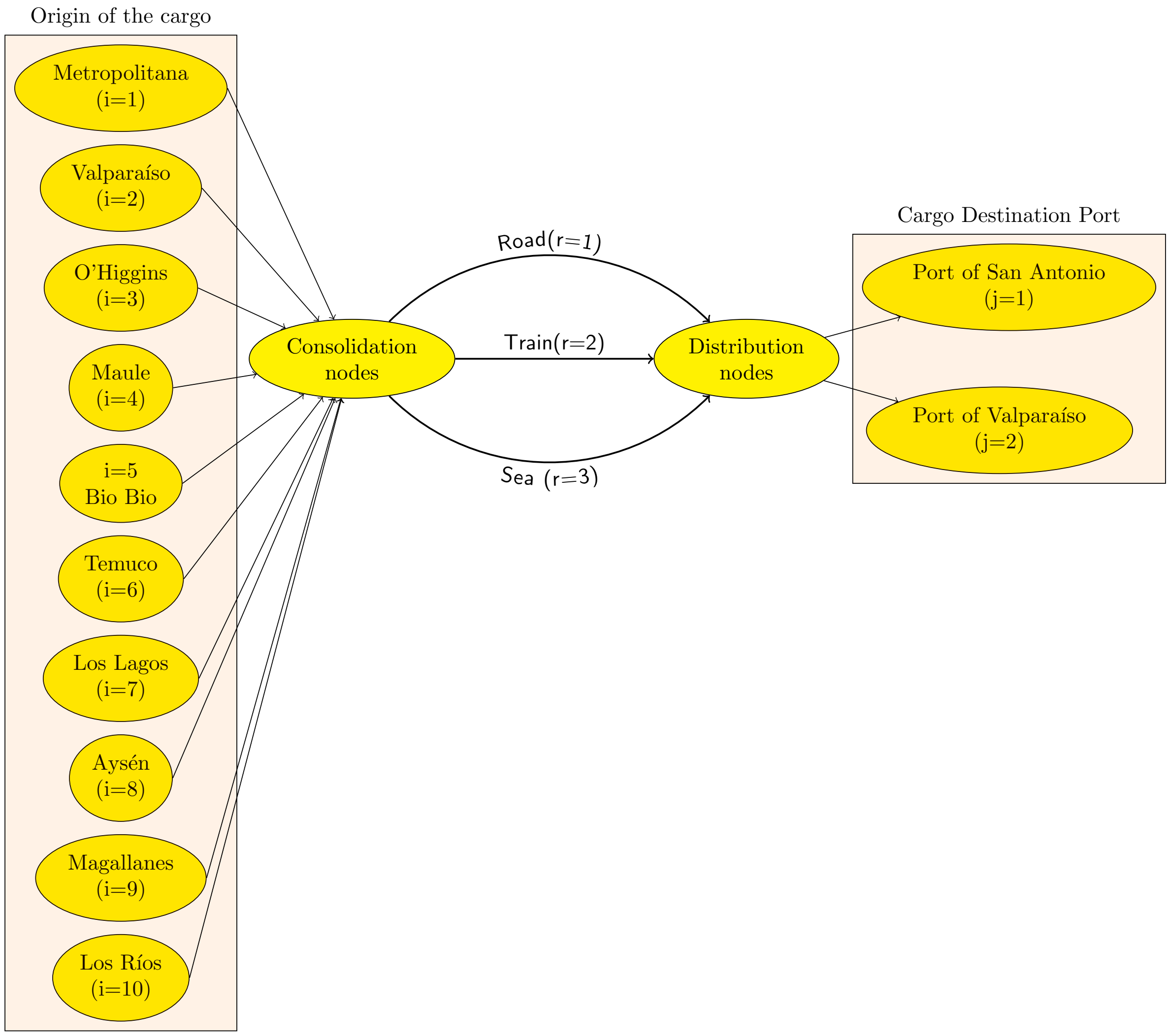

Figure 2. Conceptual diagram multimodal system.

The model consists of various entities representing its indexes:

- Zones of origin of the load (index i):
  - Metropolitan Region, Santiago (i=1),
  - Valparaíso Region, Valparaíso (i=2),
  - O'Higgins Region, Rancagua (i=3),
  - Maule Region, Talca (i=4),
  - Bío Bío Region, Concepción (i=5),
  - Temuco Region, Temuco (i=6),
  - Los Lagos Region, Puerto Montt (i=7),
  - General Carlos Ibáñez del Campo Region of Aysén, Coyhaique (i=8),
  - Magallanes and Antarctica Chilen Region, Punta Arenas (i=9)
  - Los Lagos Region, Valdivia (i=10)
- Port cargo destination zones (index j):
  - San antonio (j=1),
  - Valparaíso (j=2)
- Consolidation node installation zones (index k):
  - Metropolitana Region, Santiago (k=1),
  - Valparaíso Region, Valparaíso (k=2),
  - O'Higgins Region, Rancagua (k=3),

- Maule Region, Talca (k=4),
- Bío Bío Region, Concepción (k=5),
- Temuco Region, Temuco (k=6),
- Los Lagos Region, Puerto Montt (k=7),
- General Carlos Ibáñez del Campo Region of Aysén, Coyhaique Region(k=8),
- Magallanes and Antarctica Chilen Region, Punta Arenas (k=9)
- Los Lagos Region, Valdivia (k=10)

• Distribution node zones (index m)
  - San Antonio (m=1),
  - Zeal Zone of Valparaíso (m=2),
  - Midpoint between San Antonio and Valparaíso (m=3),
  - Calera (m=4)

• Modes of transport (index r):
  - Road (r=1),
  - Train (r=2),
  - Ship (r=3)

• Type of product (index p):
  - General cargo (p=1),
  - Refrigerated cargo (p=2),
  - Liquid cargo (p=3),
  - Bulk cargo (p=4)

Table 2 y 3 presentan parámetros y variables.

Table 2. Parameters.

Symbol	**Description**
W_{ijp}	Transport of cargo from origin node i to port of embarkation j for product type p.
$C1_{ik}^{pr}$	Unit cost of transport from the origin node i to the consolidation node k for product type p along route r [dollars per ton-kilometer].
$C2_{km}^{pr}$	Unit transport cost from consolidation node k to distribution node m for product type p on route r [dollars per ton-kilometer].
$C3_{mj}^{pr}$	Unit cost of transportation between distribution node m and port j for product type p along route r [dollars per ton-kilometer]
$C4_{im}^{pr}$	Unit transport cost from origin node i to consolidation node m for product type p via the route.
$C5_{kj}^{pr}$	Unit transport cost from origin node i to consolidation node m for product type p via the route r.
$d1_{ik}$	Generic expression for the distance between the origin node i and the consolidation center at node k.
$d2_{kj}$	Generic expression for the distance from consolidation center k to destination node j.
$d4_{mj}$	Generic expression for the distance from consolidation center m to destination node j.
$d6_{km}$	Generic expression for the distance between the consolidation center k and the distribution center at node m.
Cc_k	Investment for the setup, operation, and maintenance of a consolidation node.
Cd_m	Investment for the setup, operation, and maintenance of a distribution node.
a	Project evaluation period.

Table 3. Variables.

Symbol	Description
$x0_{ij}^{pr}$	A binary variable that equals 1 if product type p is shipped directly from origin i to destination j via route r, and 0 otherwise.
$x1_{ik}^{pr}$	Binary variable is 1 if transport is from origin i to node k for product type p via route r, otherwise 0.
$x2_{kj}^{pr}$	Binary variable equals 1 if cargo is transported from node k to j for product type p along route r, and 0 otherwise.
$x3_{km}^{pr}$	Binary variable is 1 if cargo moves from consolidation node k to distribution node m for product type p via route r, else 0.
$x4_{mj}^{pr}$	Binary variable equal to 1 if the cargo is transported from node m to port j for product type p via route r, and 0 otherwise.
$x5_{kj}^{pr}$	Binary variable is 1 if cargo is transported from node k to port j for product type p via route r, and 0 otherwise.
$z1_k$	Binary variable that is 1 if a consolidation node is installed at node k, otherwise 0.
$z2_m$	Binary variable is 1 if a distribution node is installed at node m, and 0 otherwise.
y_0	Binary variable: 1 if no consolidation or distribution nodes are installed, 0 otherwise.
y_1	Binary variable set to 1 for installing consolidation node at node k and distribution node at node m, otherwise 0.
y_2	A binary variable indicating 1 for a distribution node installation at node m, and 0 otherwise.
y_3	Binary variable equal to 1 if a consolidation node is installed at node k, otherwise 0.

3.2. Objective Function

The objective function integrates six terms: The first two penalize the cost of opening and operating a distribution and cargo consolidation center for 20 years. The remaining four, linked to potential solutions of the problem, incorporate binary variables (with a value of 1 if the solution is employed and 0 otherwise). For example, the third term, multiplied by the binary variable y_0, represents a solution that excludes distribution and consolidation nodes. The fourth term represents the interaction between a distribution center at node k and a consolidation center at node m, multiplied by the binary variable y_1. The fifth term refers to the solution that consolidates at a single node, k, represented by y_2. Finally, the sixth term implies a unique solution with a consolidation center at node m, represented by the variable y_3.

$$
\begin{aligned}
\text{Min: } & \sum_k Cc_k * z1k + \sum_m Cd_m * z2m + \\
& y_0 * \left(\sum_i \sum_j \sum_k \sum_m \sum_p \sum_r a * w_{ij}^p C6_{ij}^{pr} d5_{ij} * x0_{ij}^{pr} \right) + \\
& y_1 * \left(\sum_i \sum_j \sum_k \sum_m \sum_p \sum_r a * w_{ij}^p C1_{ik}^{pr} d1_{ij} * x1_{ik}^{pr} + a * w_{ij}^p C2_{km}^{pr} d6_{km} * x3_{km}^{pr} + a * w_{ij}^p C3_{mj}^{pr} d4_{mj} * x4_{mj}^{pr} \right) + \\
& y_2 * \left(\sum_i \sum_j \sum_k \sum_m \sum_p \sum_r a * w_{ij}^p \left(C4_{im}^{pr} d3_{im} * x5_{im}^{pr} + C3_{mj}^{pr} d4_{mj} * x4_{mj}^{pr} \right) \right) + \\
& y_3 * \left(\sum_i \sum_j \sum_k \sum_m \sum_p \sum_r a * w_{ij}^p \left(C1_{ik}^{pr} d1_{ik} * x1_{ik}^{pr} + C5_{kj}^{pr} d2_{kj} * x2_{kj}^{pr} \right) \right)
\end{aligned}
\tag{1}
$$

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Subject to:

$$y_0 + y_k + y_m + y_{km} = 1 \tag{2.1}$$

$$x1_{ik}^{pr} \leq z1_k \forall k \tag{2.2}$$

$$x2_{kj}^{pr} \leq z1_k \forall k \tag{2.3}$$

$$x3_{km}^{pr} \leq z1_k \forall k \tag{2.4}$$

$$x3_{km}^{pr} \leq z2_m \forall k \tag{2.5}$$

$$\sum_k z1_k \leq 1 \tag{2.6}$$

$$\sum_m z2_m \leq 1 \tag{2.7}$$

$$x0_{ij}^{pr} + x1_{ik}^{pr} + x5_{im}^{pr} = 1 \tag{2.8}$$

$$x0_{ij}^{pr} \leq y_0 \forall i, j \tag{2.9}$$

$$x1_{ik}^{pr} \leq y_3 \forall i, k \tag{2.10}$$

$$x2_{kj}^{pr} \leq y_3 \forall k, j \tag{2.11}$$

$$x3_{km}^{pr} \leq y_3 \forall k, m \tag{2.12}$$

$$x3_{km}^{pr} \leq y_2 \forall k, m \tag{2.13}$$

$$x4_{mj}^{pr} \leq y_2 \forall m, j \tag{2.14}$$

$$x5_{im}^{pr} \leq y_2 \forall m, i \tag{2.15}$$

Constraint 2.1 limits the choice to a single solution among the four possible ones, represented by the variables y_0, y_1, y_2, y_3. Constraint 2.2 ensures the connection from the source node i to the consolidation node k only if the latter is operational. Constraint 2.3 establishes transit from consolidation node k to destination node j only if k is operational. Constraint 2.4 ensures the connection of node k to m only when consolidation node k is operational. Constraint 2.5 guarantees transit from node k to node m only when the latter is operational. Constraint 2.6 ensures the existence of at most one distribution center. Constraint 2.7 limits the number of consolidation centers to one. Constraint 2.8 ensures that cargo transportation proceeds directly from the source node i to a final destination j, or through consolidation nodes k or m. Constraint 2.9 establishes that direct cargo transportation from i to j is feasible only if binary variable y_0 is one; otherwise, this route is discarded. Constraint 2.10 guarantees that cargo transportation from source node i to consolidation node k is only feasible if binary variable y_3 is one; otherwise, this transportation is unviable. Constraints 2.11 and 2.12 specify that cargo can only be transported directly from k to destination node j and distribution node m, respectively, under the same condition of y_3 being one. Constraint 2.13 determines that cargo transportation from node k to distribution node m is only allowed if y_2 is one, prohibiting it otherwise. Constraint 2.14 ensures direct cargo transportation from node m to destination node j only when binary variable y_2 is one. Constraint 2.15 ensures a similar condition for transportation from node i to distribution node m. If it is not one, the corresponding transportation is not allowed.

The proposed model, based on the Hub and Spoke strategy and without a predefined value of p, overcomes the limitations of a fixed number of hubs, providing flexibility in the allocation of stations for cargo consolidation or deconsolidation. This adaptability is evidenced in Figure 2, where two optional hubs are highlighted, whose selection depends on factors such as cargo, costs, and distances.

Given Chile's elongated geography, it is suggested to locate these hubs in strategic regions: one in the central-south and another in a central area close to the main ports.

4. Optimization Data for the Chilean Multimodal System

4.1. Freight Transport Data: Distances and Volumes

Tables 4 and 5 present the 2019 TEU loads transported from regional cities to the ports of San Antonio and Valparaíso, respectively [47].

Table 4. Cargo transportation from origins to San Antonio Port [TEUS] [47].

id	Region, Capital city	General	Refrigerated	Liquid	Granel
1	Metropolitan Region, Santiago	7,543,212	640,633	15,897	17,683
2	Valparaíso Region, Valparaíso	880,155	1,153,233	19,576	0
3	O'Higgins Region, Rancagua	1,491,447	3,949,870	6456	0
4	Maule Region, Talca	2,457,589	1,545,269	22,395	0
5	Bío Bío Region, Concepción	320,855	48,966	144	179,314
6	Temuco Region, Temuco	4345	58,460	0	0
7	Los Lagos Region, Puerto Montt	27,845	48,016	0	0
8	General Carlos Ibáñez del Campo Region of Aysén, Coyhaique	8914	60,266	0	0
9	Magallanes and Antarctica Chilen Region	38,078	210,935	0	0
10	Los Ríos Region, Valdivia	24,358	12,794	0	0

Table 5. Cargo transportation from origins to Valparaíso Port [TEUS] [47].

id	Region, Capital city	General	Refrigerated	Liquid	Granel
1	Metropolitan Region, Santiago	4,133,243	530,133	6408	1
2	Valparaíso Region, Valparaíso	773,020	991,239	67,241	0
3	O'Higgins Region, Rancagua	673,554	3,208,655	2836	0
4	Maule Region, Talca	809,974	749,697	15,123	45
5	Bío Bío Region, Concepción	39,073	22,206	2133	0
6	Temuco Region, Temuco	22,980	22,543	0	0
7	Los Lagos Region, Puerto Montt	7486	15,817	0	0
8	General Carlos Ibáñez del Campo Region of Aysén, Coyhaique	0	2185	0	0
9	Magallanes and Antarctica Chilen Region, Punta Arenas	531	6863	0	0
10	Los Ríos Region, Valdivia	1769	1646	0	0

Tables 6, 7 and y 8 respectively present the distances between the origin nodes and the consolidation nodes, the origin nodes and the distribution locations, as well as between the consolidation nodes and the shipping ports.

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Table 6. Distances between origin and cargo consolidation nodes[1].

id	Region	(1) RM [2]	(2) Valparaíso	(3) O'Higgins	(4) Maule	(5) Bio Bio	(6) Temuco	(7) The Lakes	(8) Aysén	(9) Magallanes	(10) Los Lagos
1	Metropolitan	0	116	84	257	500	690	1036	1898	3023	855
2	Valparaíso	116	0	194	367	610	800	1203	2066	3191	1023
3	O'Higgins	84	194	0	173	416	606	948	1810	2935	767
4	Maule	257	367	173	0	247	437	777	1639	2764	596
5	Bio Bio	500	610	416	247	0	305	644	1506	2632	464
6	Temuco	690	800	606	437	305	0	353	1215	1255	172
7	Los Lagos	1036	1203	948	777	644	1032	0	1042	2167	211
8	Aysén	1898	2066	1810	1639	1506	1215	1042	0	1254	1073
9	Magallanes	3023	3191	2935	2764	2632	1255	2167	1254	0	2199
10	Los Ríos	855	1023	767	596	464	172	211	1073	2199	0

[1] Calculate the distance between cities in Chile. https://sitios.cl/servicios/distancias.htm, access 26/3/2024..
[2] RM: Metropolitan Region

Table 7. Distances between initial, final and intermediate distribution nodes[1].

id	Origin node [2]	San Antonio [3]	Valparaiso [3]	Center of gravity [4]	La Calera
1	Metropolitan	117	125	121	127
2	Valparaíso	88	10	39	47
3	O'Higgins	141	98	120	208
4	Maule	265	366	315	381
5	Bio Bio	508	609	558	624
6	Temuco	698	810	754	815
7	Los Lagos	1040	1142	1091	1143
8	Aysén	1717	1818	1767	1833
9	Magallanes	3012	3123	3067	3128
10	Los Ríos	856	957	906	958

[1] Calculate distance between cities in Chile https://sitios.cl/servicios/distancias.htm, access 26/3/2024.
[2] Consolidation. [3] Final destination and possible distribution node. [4] Possible distribution node.

Table 8. Distances between potential consolidation nodes and shipping ports[1]

Origin	San Antonio	Valparaiso (Zeal[2])
San Antonio	0	88
Valparaiso (Zeal)	88	10
Center of gravity	8	8
Calera	113	57

[1] Calculate the distance between cities in Chile https://sitios.cl/servicios/distancias.htm, access 26/3/2024.
[2] Logistics Support Extension Zone.

4.2. Costs of Different Means of Transportation

Table 9 summarizes the variable costs of railway transportation for both cargo and containers in the south of Chile. Additionally, Table 10 and Table 11 present the unit costs of road and maritime transportation, respectively, based on the type of cargo. A fixed exchange rate of 700 CLP per dollar [48] is applied.

Table 9. Rail transportation costs for different types of cargo 2018 [ton-km]

Cargo	Trailer	Cost [CLP/tn-km]	Cost [dollars/tn-km]
General	Flat Trolley	24	0.03428
Refrigerated	Reefer container	26	0.03714
Liquid	Pond	25	0.03571
Granel	Bulk hopper	24	0.03428

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Table 10. Road transportation costs for different types of freight 2018 [km-ton]

Cargo	Tractor	Cost [CLP/tn-km]	Cost[dollars/tn-km]
General	Flat	49	0.070
Refrigerated	Refrigerated	53	0.075
Liquid	Pond	52	0.074
Granel	Hopper	53	0.0757

Table 11. Maritime transportation costs for different types of cargo $[tn - km]$ [1]

Cargo	Storage	Cost [CLP/tn]	Cost [dollars/$tn - km$][2]
General	Container	145	0.007631579
Refrigerated	Container reef	175	0.009210526
Liquid	Pond	58	0.003052632
Granel	Pond	35	0.001842105

[1] shipping cost information [49].
[2] Average international trade values, calculated on the basis of the most frequent trip to Beijing, China, indicate a distance of 19,000 km.

4.3. Warehousing Costs

To obtain the storage costs shown in Table 12, the reference data from the Barrancas multimodal terminal are used. This terminal is primarily intended for the Costanera Espigón dock at the Port of San Antonio, which is under construction by DP World [50].

Table 12. Costanera Espigón Pier [50].

Items	Values	Units
Investment	19	millions of dollars
Warehouse capacity	250.000	TEU/año
Train capacity	600	mt de largo

5. Results

The results presented in Table 13 are derived from the data contained in Tables 5 to 12 and are based on the proposed mathematical model, consisting in a non-linear integer binary programming. This model employs 2,369 binary variables and 6,932 constraints, implemented in GAMS [51] and solved using SCIP version 3.1 [52] in the same environment, through a specific MIQCP routine of SCIP.

Table 13. Optimisation results.

		San Antonio				Valparaíso			
Region	Tipo	**General**	**Reeffer**	**Liquid**	**Granel**	**General**	**Reeffer**	**Liquid**	**Granel**
1 RM	Train	1	1	1	1	1	1	1	1
2 Valparaiso	Road	0	0	0	1	0	0	0	1
2 Valparaiso	Train	1	1	1	0	1	1	1	0
3 O'Higgins	Road	0	0	0	1	0	0	0	1
3 O'Higgins	Train	1	1	1	0	1	1	1	0
4 Maule	Road	0	0	0	1	0	0	0	0
4 Maule	Ship	1	1	1	0	1	1	1	1
5 Bio Bio	Road	0	0	0	0	0	0	0	1
5 Bio Bio	Ship	1	1	1	1	1	1	1	0
6 Temuco	Road	0	0	1	1	0	0	1	1
6 Temuco	Ship	1	1	0	0	1	1	0	0
7 Los Lagos	Road	0	0	1	1	0	0	1	1
7 Los Lagos	Ship	1	1	0	0	1	1	0	0
8 Aysén	Road	0	0	1	1	1	0	1	1
8 Aysén	Ship	1	1	0	0	0	1	0	0
9 Magallanes	Road	0	0	1	1	0	0	1	1
9 Magallanes	Ship	1	1	0	0	1	1	0	0
10 Los Ríos	Road	0	0	1	1	0	0	1	1
10 Los Ríos	Ship	1	1	0	0	1	1	0	0

The results indicate that, for the metropolitan region, the transport of cargo by rail to both ports is the most appropriate. In regions five and six, bulk cargo shipping via train is advised, while road transport proves more efficient for other cargo types. Conversely, in the seventh region, maritime transport to both ports is preferred for most cargo types, with the exception of bulk cargoes destined for San Antonio, which are better served by road.

For the eighth region, maritime transportation is favored, while regions nine through fourteen demonstrate enhanced efficiency through a blend of maritime and land transport. Notably, the model eschews cargo consolidation or distribution centers due to the substantial volume of cargo (39.4%) originating from the metropolitan region, situated further north. Establishing centers there would entail redundant movements and an additional estimated cost of 19 million per center.

Over a 20-year span, the solution without centers incurred costs of 2.626 billion, representing only 30% compared to the 8.642 billion from an exclusively road transport model. Furthermore, this multimodal strategy led to a notable reduction in CO_2 emissions, totaling 12,794 tons compared to the 66,190 tons generated by the current model, reflecting a decrease of 19.3%. It's important to note that this analysis factored in a 30-kilometer increase in road transportation for all regions from their respective capitals.

6. Discussion and Conclusions

6.1. Optimization Model

The classical "hub and spoke" model is applied to logistic networks through hubs that function as multimodal warehouses. In the study of the model applied to Chile, the optimal solution dispenses with these hubs, favoring a hub-less exchange approach. This mathematical model, which distinguished between concentrating and deconcentrating hubs, opted for a multimodal strategy with multiple modes of transportation. This decision is justified by Chile's elongated geography and the clustering of cargo generators near Santiago, the capital[53].

The application of this research addresses an adaptation of the hub and spoke model to the specific context of a country with territorial concentration in cargo generation and distribution. The general version of the model, in its p-hub version, selects an optimal quantity of hubs[54]. However, given the country's particular geographical characteristics, the possibility of establishing a maximum of two hubs was considered: one in the south to concentrate cargo and another in the central zone, near the ports, for unloading. Contrary to this hypothesis, the optimal results of the model suggest dispensing with these hubs, favoring direct transportation of cargo from generation points to ports. This approach not only optimizes logistics but also significantly contributes to reducing greenhouse gas emissions.

6.2. Multimodal System

This study emphasizes the need to optimize road transportation in Chile, especially in the central and southern regions of the country, and contrasts its advantages and limitations with those of railway and maritime transportation. It is highlighted that, although the railway is efficient for large volumes and long distances, and maritime transport excels in certain conditions, each mode has specific characteristics and costs that influence logistics efficiency [55].

The State Railways Company (EFE) plays a key role in logistics, connecting productive regions with ports, but faces challenges such as the lack of direct connections in some areas. Railway transport is highlighted for its sustainability, especially when using renewable energies, offering an alternative with lower environmental impact compared to road transport [56]. However, limited flexibility and the need for truck transshipment, which increases loading and unloading costs, mark disadvantages compared to the versatility of road transport.

In terms of operational efficiency and CO2 emissions, railway transport, powered by unconventional renewable energies (ERNC), emerges as a significantly cleaner option compared to the emissions capacity of the truck fleet [57].

In conclusion, the optimization of transportation in Chile requires a strategic integration of road, railway, and maritime modes, aiming to maximize efficiency, sustainability, and emissions reduction in freight transportation.

6.3. Future Research

Exploring the impact of integrating emerging technologies, such as automation and digitization, on the efficiency of multimodal transportation is essential. In the future, it will be possible to assess the viability of replicating the model in regions with similar geographical and logistical characteristics, adapting solutions to different national or international contexts. Additionally, investigating the role of public-private cooperation in the development and implementation of these transportation solutions, analyzing their long-term socioeconomic and environmental impact, is crucial. In this context, considering a new routing model and possible consolidation, integrating it with neighboring countries in the multinational project "bioceanic corridor," involving Argentina, Brazil, Chile, and Paraguay, is proposed[58].

In a forthcoming study, the impact of increased volume in Chile's ports and cities could be evaluated, considering both economic benefits and potential port overloads. It is essential to analyze the current infrastructure's capacity to efficiently manage the anticipated increase in international cargo, using a routing model with limited capacity that considers customs restrictions and points of loading.

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Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	Directory of open access journals
TLA	Three letter acronym
LD	Linear dichroism

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