sustainability

MDPI

Article

Designing a Geo-Strategic Railway Freight Network in Brazil Using GIS

Cassiano A. Isler [1], Yesid Asaff [2] and Marin Marinov [3,*]

[1] Transportation Engineering Department, Escola Politécnica, University of São Paulo, São Paulo 05508-070, Brazil; cassiano.isler@usp.br
[2] Mobility Engineering Department, Federal University of Santa Catarina, Joinville 89219-600, Brazil; yesid.a@ufsc.br
[3] School of Engineering and Applied Science, Engineering Systems and Supply Chain Management, Aston University, Birmingham B4 7ET, UK
* Correspondence: m.marinov@aston.ac.uk

Abstract: The sustainable development of geo-strategic transport networks plays a key role to meet the current expansion of the demand for commerce and economic growth. In this paper, a new geo-strategic railway network for freight services is designed with the purpose of meeting the needs of current and future demands for freight transport in the state of Santa Catarina, South Brazil. The freight flows of bulk cargo, containers, and refrigerated and liquid cargo observed in 2005 and 2015 and expected for 2023 have been analyzed and assigned to a fully connected railway network. The number of trains to meet all the demands has been identified. The links that would have a minimum number of daily trains running on them have also been identified and analyzed. New assignments are proposed and visualized using GIS. Next, location and technical specifications of specialized intermodal terminals focused on the customers' and operators' needs are discussed. The study shows that technological specifications for terminal operations play an important role when dealing with multiple freight types and contribute to better use of the existing infrastructure.

Keywords: geo-strategic railway network design; freight transport; intermodal terminal; GIS

Citation: Isler, C.A.; Asaff, Y.; Marinov, M. Designing a Geo-Strategic Railway Freight Network in Brazil Using GIS. *Sustainability* **2021**, *13*, 85. https://dx.doi.org/10.3390/su13010085

Received: 22 October 2020
Accepted: 16 December 2020
Published: 23 December 2020

1. Introduction

The world is currently facing an expanding demand for economic growth and commerce. For this demand to be accommodated there is a need for developing a more efficient way of easing the distribution of freight nationally and internationally. The well-settled congestion on Brazilian motorways, in and around its cities, the time wasted in traffic jams [1,2], the concerns of ever-growing environmental effects generated by road traffic [3,4], and the increase in fuel consumption [5] are some of the symptoms suggesting that the transport system in the country needs thorough revision.

Brazilian cities are barely connected with rail; hence, it has not yet experienced the benefits of a robust rail network service in place. That is why it is timely and needed to study the potential design and implementation of rail network services, which would improve the transport of different types of freight. This will then bring significant improvements to the community, the environment, and its economic growth. In this context, [6] provided some insights on how to increase the competitiveness of the rail sectors for freight transport in Europe, aiming for sustainable long-term competition through the supply chain integration by the application of innovative rail freight services. In Brazil, [7] ranked the investments in new railways according to their expected economic and environmental contributions, simulating the flows of soybean and corn production and obtaining the reduction in transportation costs and CO_2 emissions.

According to [8], a transport infrastructure initiative is capable of fulfilling the government policies, facilities, trade, capital, and cultural exchange gaps among economies, more specifically in the Eurasian trade routes studied by the authors. In Brazil, the strategic location of the state of Santa Catarina connects the southern region of the country (the states of Rio Grande do Sul and Paraná) to the international markets through its ports and also facilitates the trades between the countries in South Latin America (Chile, Argentine, and Paraguay), and the other Brazilian states, especially in the Southeast, where the most populated and industrialized regions of the country are located (states of São Paulo, Minas Gerais, Espírito Santo, and Rio de Janeiro).

In this paper, a geo-strategic railway network for freight services is designed with the purpose of current and future freight transport in Santa Catarina, South Brazil. Such infrastructure would increase the trades within the Brazilian state, among their regions and the other states, and also with the international market.

More specifically, we propose a set of new railway connections represented by links connected to nodes expected to provide specific services to meet the requirements of freight transport among the regions of Santa Catarina. These nodes are described as hubs connecting all of its major regions, hence providing alternative sustainable services to the currently dominant transport by roads.

The potential of transporting different types of freight by rail, from bulk aggregates to low density high value goods, reveals the suitable layout for the new rail freight services proposed. To understand the behavior of the current freight flows in the state of Santa Catarina, accurate data sets were collected and analyzed. This activity made it possible to identify the cities and regions with higher potential for new rail freight services.

To visualize the data sets collected and so to build different layouts of a new rail freight network service, the use of suitable Geographic Information System (GIS) software was appropriate to describe different scenarios and to match them with the geographical features of the state of Santa Catarina. The results obtained take the shape of oriented graphs consisting of nodes replicating the major hubs in the network and links connecting the nodes [9]. An all-or-nothing assignment model resulted in estimates of freight flows for each link. Next, the size of freight flows has been studied to propose the rationale of the railway network expansion and to evaluate the potential of each node for a rail-based service.

This paper is organized as follows. After this introduction, we provide a discussion on service network design models, their functionalities, and visualization with GIS software applications. Section 3 offers a description of the up-to-date concepts of intermodal terminals. The dataset used to estimate the freight flows between major regions in Santa Catarina is presented in Section 4, followed by the procedure of generating a strategic rail network for freight transport in the state and the outcome of our research in terms of terminal location. Conclusions and avenues for further studies are explored in Section 5.

2. Literature Review

Interest in regional freight transport planning is increasing in the literature. Ref. [10] proposed a tactical intermodal container flow approach to control and to reassign containers in the context of intermodal freight transport planning problems among deep-sea terminals and inland terminals in hinterland haulage. Ref. [11] developed a short/mid-term agent-based model for intermodal freight transport chains on a rolling horizon and applied it to a rail-truck network consisting of six intermodal corridors, each connecting a pair of intermodal terminals.

The relationship between freight transport and economy in the Chinese market was investigated by [12], who found that the industrial structure and geographical characteristics of each region affect the decline of the contribution of high freight-demand sectors to the economic development in the country. The authors state that region-dependent infrastructure improvements will lead managers to realize the mutual benefits to the development of transportation and the economy.

Ref. [13] used Stated and Revealed preference data to model and assess the social impacts of rail infrastructure investments in Argentina by considering the Free Alongside

Ship price, freight transport cost, travel time, and lead time as relevant variables to estimate non-deterministic willingness to pay measures for a cost–benefit analysis.

Terminal location problems have also been a topic of interest among researchers recently. Ref. [14] denote two mainstreams of intermodal freight terminal research—quantitative studies to optimize the number of terminal locations across the transport network (e.g., [15]) and studies focused on governance and planning for developing multimodal services to improvements on freight distribution by rail transport (e.g., [16,17]). While [18,19] considered economic criteria for locating freight terminals over a network, and [20] included economic and environmental aspects to the problem, [14] proposed a framework to assess the sustainability of multimodal freight terminals including the social, technical, economic, environmental, and political dimensions.

For network design and modeling purposes, a transport network may be represented by a directed or undirected graph, where the nodes of the network depict the yards, terminals, stations, and junctions, and links show how nodes are connected by railway tracks. Nodes in the network may generate, absorb, and/or have products flowing through them. Each node and link are described by limited physical and operating capacity. Maximum capacity can be measured in number of trains served over a given period of time. The levels of utilization of every node and link can be measured by Key Performance Indicators (KPIs); for example, the percentage of time it has been occupied.

Service network design is a task which is required when a client demands new services in a rail network [21]. As research in this area deals with an existing network, it is important to be aware of network physical characteristics, the possible physical routes, and location of facilities, especially when this network is designed for single wagon load services [22,23].

Optimization network models integrate the challenges associated with solving service network design and traffic distribution problems (see [24–27]). Optimizing network models are employed to analyze multiple-flow routes through complex congested networks. They are quite effective in identifying the bottlenecks in such networks. For example, [28] studied a railway network design problem when looking at network investment, transportation services, and carbon emission costs caused by highway and railway. The authors proposed a bi-level programming model for the Railway Network Design Problem (RNDP), where a scheme of railway network planning alternatives is generated by solving a network flow assignment problem. Ref. [29] evaluated the impact of infrastructure improvements and capacity expansion on a railway network to increase freight transportation by solving a bi-objective mathematical model to minimize the cost related to infrastructure investments, and maintenance and operating costs.

Besides, some concepts and modeling approaches from the classic four-stage transport model [30] may be applied to the traffic distribution problems, mainly to the stages related to modal split and network loading. For example, [31] proposed a dynamic modal split model to a multimodal freight transport system based on the paradigm of random utility to estimate the demand on various transport modes over time. Ref. [32] proposed a mathematical model of traffic flow distribution over a network focused on the external costs of air pollution and analyzed the resulting flows to the development of an environmentally friendly transportation system.

Service network design is defined as a repetitive regrouping of traffic as it goes towards its final destinations [33]. Regrouping takes place in transport hubs. Service network design shows how transport units travel through the components of a transport network (terminals, yards, lines). The logic incorporated in it is that transport hubs act as facilities which attract flows; hence, the bigger the facility the greater the flow it attracts.

Service network design makes it possible to set up tactical decisions about the selection and scheduling of the new services to be introduced, the specification of terminal operations, and the routing of freight. The corresponding models are usually specified as network design formulations, a class of mixed-integer network optimization problems [34]. Contributions to service network design in the literature are reported by [35–39].

In addition to service network design, there are hub network models which look at defining a distribution system in which hubs for transhipment and sorting of freight and non-hub nodes are identified in such a way to guarantee economies of scale for inter-hub transportation [40]. An extensive review on hub network design problems can be found in [41,42].

Ref. [43] examined the network equilibrium and system optimum problem in a network with discrete distributions of Values of Time (VOT). While [44–47] discussed the importance of VOT and its distribution for travelers' route choice decisions, [40] proposed a hub network for freight transport based on discrete distributions of VOT from a stated preference survey in China by solving a single p-hub median problem with a simulated annealing algorithm. More recently, [48] included VOT and Value of Reliability (VOR) measured from a Stated Preference survey to solve a service network design problem targeting service performance improvement on a case study in China and concluded that users' total generalized cost is reduced while service levels improve when variations in shippers' VOT and VOR are taken into account.

If the network design problem is modeled as a traffic allocation problem, then the costs over the links of the network may be modeled as a function of the flows through it, and a system optimum or user equilibrium may be considered [49]. However, if congestion is not relevant to travel times over the links of a network, it can be modeled assuming constant cost in each link [50].

Besides, both approaches are modeled as optimization problems and would be solved analytically; the flow-dependent cost approach requires special algorithms given the non-linearity of the objective function for non-theoretical large networks. However, the fixed cost network typically requires an all-or-nothing assignment procedure from successive applications of a shortest path algorithm [51].

Due to the simplicity, it sometimes appears to be fairly easy to study changes in complex transport networks by optimization network models. In many cases, though, they may be too abstract and there is risk for them not to face realism. In such cases, simulation network models ought to be used [52].

On the other hand, less sophisticated planning tools and approaches in terms of mathematical complexity and implementation efforts can be applied to the analysis of transport infrastructure improvements. In this sense, Geographic Information Systems (GIS) are useful in visualizing complex transport networks and solving network problems regarding design and traffic allocation. More specifically, one can apply the GIS tools to propose a new transport infrastructure based on freight or passenger estimations among geographical regions depicted as nodes of a graph.

Ref. [53] explained that, from 1988 to the 2000s, the World Bank and the Chinese Ministry of Railways (MOR) had been building, using, and improving a Spatial Decision Support System (SDSS) for railway investment planning. The goal of the Railway Investment Study (RIS) was to evaluate capacity expansion strategies and prioritize the investments for medium term (15 years) planning. The SDSS addresses a network design model which simultaneously proposes new links between cities and assigns traffic to the network in a cost minimizing fashion, which is integrated to the RGIS (Railway GIS) that can: display data on maps or charts; edit maps, network, and databases; query databases; calculate shortest paths; and switch between the national map and more detailed maps.

Ref. [54] developed a GIS-based methodology for assessing the potential locations of terminal park-and-ride facilities (free, paved parking lots where commuters leave their cars and change modes to some form of mass transit) along urban rail lines, which differs from political-based approaches and traditional travel demand modeling in its use of an objective measure of accessibility.

Ref. [55] proposed a method for optimizing the choice of the corridors of High Speed Rail (HSR) based on "multi criteria analysis" with GIS support and applied it to a real case in Italy in order to evaluate its economic feasibility, and social and environmental impact. On the other hand, [56] determined optimal railway routes using remote sensing (land use, geology, slope, and topographic maps), GIS layers relating to hydrology and transportation networks, and the results of questionnaires administered to experts and professionals to obtain responses regarding the importance of various factors in least cost path determination.

In a more comprehensive approach, [57] reviewed the systematic integration of BIM (Building Information Modeling) with GIS in the railway construction scope, with the aim of analyzing the need for this integration and its benefits. The authors state that, although BIM has significant features, it has been restricted to building information (indoor environment). The authors state the integration with GIS can provide a complete toolset to integrate interior and exterior information to provide a complete picture of the built environment and to support collaboration between participants for better collaborative decision making throughout the lifecycle of a railway project.

3. Up-to-Date Concepts on Terminal Requirements

The freight transport market has been changing, with cargo being transported by trains composed by blocks, often smaller and more frequent trains, in faster and more reliable services. This requires the application of new concepts in cargo transportation and improvements to the services to meet the needs of operators and customers [58].

Ref. [6] showed that a series of operational improvements must be applied to the railways to make them competitive with roads. Therefore, reducing the railway operating costs is vital in order to offer a competitive price, which can be achieved by strategically locating specialized terminals in the nodes of the network to improve its capacity, promote better scheduling, and, thus, result in better use of the infrastructure.

For many years, the transport industry has applied the hub-and-spoke concept, integrating multiple actors looking for cost reduction and effective service time. However, this concept is still in the stage of development and application by the rail freight sector, since it encompasses various types of terminals, connecting to each other as sources and destinations. These nodes must be close to production and/or consumption areas and traffic corridors to be capable of transforming the transit time into value to the product, reducing the cargo transfer time between modal or train to train, achieving a high coefficient of occupancy in the train, and the ability to find the best route to reach the final terminal through the integration of the entire network. These are the key elements that contribute to an efficient transport network.

The efficiency of a rail freight service is dependent on the level of service of terminals, yard screening, and feeders. Transhipment in terminals is usually carried out with vertical cranes and forklifts. With this equipment, a container can be moved from a train to a truck, and vice versa, in a costly, time consuming vertical overflow process, with risk of damage to the cargo. For efficient delivery and cargo handling, the intersection between the highway and the rail facility requires good infrastructure and logistics processes in place. Depending on the region of the intermodal operation, these intersections, also known as intermodal terminals, can serve different industries and handle the most varied types of products.

Modal transfer points require procedures and technologies with lower costs and that consume less time. Feeders (FD), also called distributors, are facilities which move smaller amounts of cargo and enable cargo consolidation and transfer to different modes to its final local consumption. On the other hand, transhipment by horizontal load transfer between trucks positioned parallel to the railroad can be performed in Small Terminals (ST), allowing trains to stop at small intervals to load or deliver a limited number of containers. Operation of this type of terminal requires fewer employees while allowing faster destination source delivery.

Such an intermodal freight rail system was implemented in Switzerland [59]. Innovatrain is a train line with multiple terminals along the railway separated by small distances, on a push-pull train system capable of operating in both directions, while the ContainerMover system is used in the horizontal overflow between the train and the truck, where the device is mounted on the truck. Swedish CarConTrain (CCT) [60] is another system that consists of a wagon traveling parallel to the track, equipped with arms that can transfer cargo horizontally. This system allows the transferring of loads from 2.5 to 3.6 m wide and from 3 to 12 m in length. Since it can be completely automated, the train can carry out the load/unloading whether the truck is in the terminal or not, allowing the train to operate at any time. The advantage is the terminal cost reduction and, consequently, the overall transportation cost.

A Container Hub-Feeder Service (CHFS) assumes larger volumes of cargo transference to gain in scale, thus allowing significant cost reductions. These are locations where multiple wagons of shuttle cargo trains are consolidated or unbundled to different destination terminals. These terminals can be connected with screening services for cargo consolidation. Instead of a conventional terminal service, it can be viewed as a linear dispatching system where the train travels on a main route and wagons are added or disaggregated at these terminals along the railroad. It should be noted that such terminals can also be a feeder for certain routes and act as a small terminal for others.

4. Case Study

In this section, we locate new railway terminals for freight transport along the existing transport network in the state of Santa Catarina, South Brazil. Specifically, we describe the geography of the state and present the existing railway network infrastructure and its services for current users. Next, we summarize the freight demand data showing the amount of freight transported within the state and the expected amount to be transported in the future. We describe the procedure for identifying and proposing new geo-strategic links and specialized nodes (FD, ST, and CHFS) of a new railway network for freight services, considering the potential needs of stakeholders and customers that would use the railway services.

4.1. The State of Santa Catarina

Santa Catarina is the 11th most populous Brazilian state with 6,910,553 inhabitants and the 20th in territorial area with 95,736.165 km^2 [61]. It is administratively divided into 295 municipalities, grouped into six mesoregions: (1) Grande Florianópolis, (2) Norte Catarinense, (3) Oeste Catarinense, (4) Serrana, (5) Sul Catarinense, and (6) Vale do Itajaí. Figure 1 shows the population density across the state, mostly concentrated in the eastern and north-eastern coast, where its capital (Florianópolis) and its largest city (Joinville) are located, respectively. Its 295 cities are administratively clustered into the 20 microregions depicted in Figure 2.

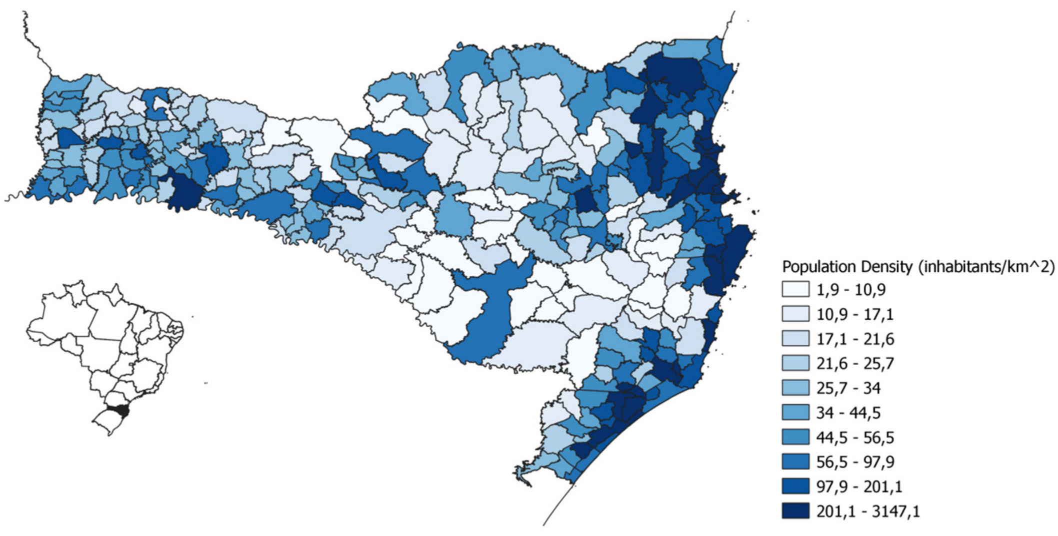

Figure 1. Santa Catarina by population density [61].

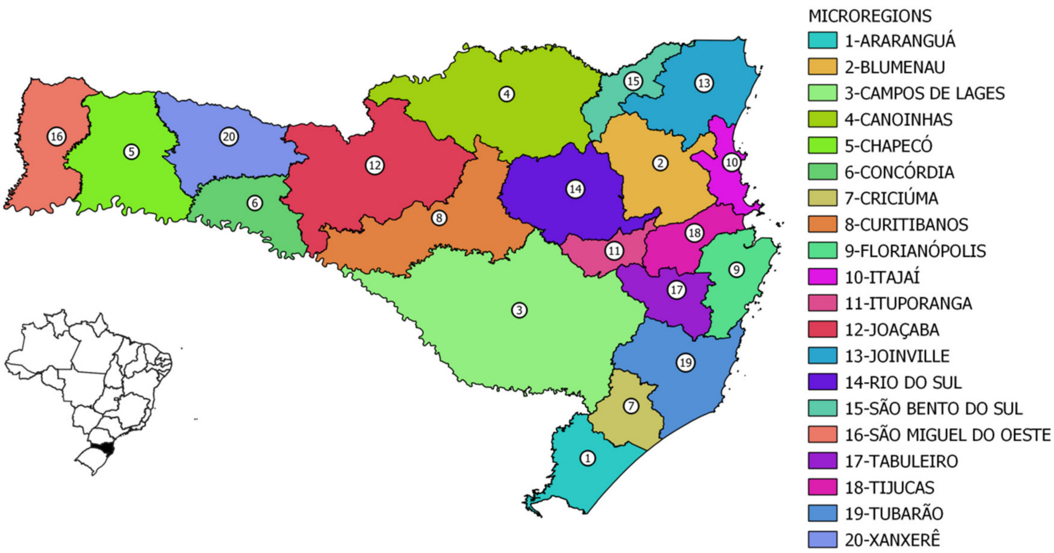

Figure 2. Microregions of Santa Catarina [62].

The concentration of activities near the coast is a consequence of its flat terrain between the ocean and a mountainous chain in the mid-west, and a rough terrain to the west, as shown in Figure 3. Freight is mainly transported from other parts of the country and from the west to the ports, through the road and rail transport routes shown in Figure 3. The railways played an important role in the land occupation and urbanization in the 20th century, and currently are used exclusively for freight transport. Trucks run on motorways owned by the State and the Federal government.

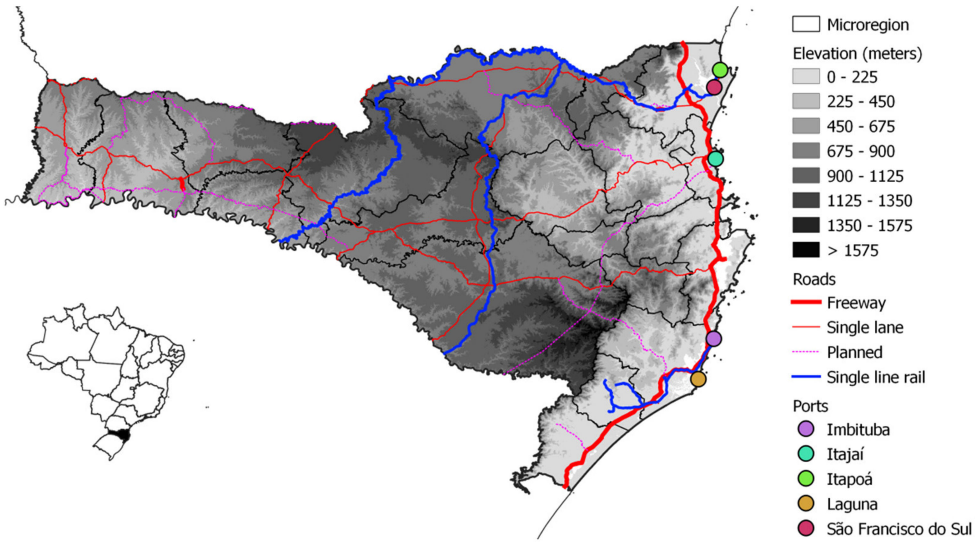

Figure 3. Transport infrastructure of Santa Catarina over terrain elevation.

4.2. Freight Flows and Network Development

The existing railway network is mainly used to transport goods from the northwest to the ports in the east, and to move freight between Brazilian states across Santa Catarina, and also from those locations to its ports. In this paper we suggest improvements to the existing network, by the inclusion of new railway links to connect the microregions of Santa Catarina, and also to integrate these regions with the operation of specific types of terminal (FD, ST, or CHFS) based on the type of freight to be transported.

Given the set of virtual center points that describes the microregions of Santa Catarina located in their respective geographic center (henceforth, named simply by nodes), we propose an initial set of links connecting them by means of a GIS tool that produces a Delaunay triangulation [63], thus providing such connections without intersections between links out of the existing nodes. Next, we analyzed the flows of products between origins and destinations represented by the nodes in three different years (2005, 2015, and expected for 2023).

We applied an all-or-nothing assignment procedure to the network resulting from the Delaunay triangulation and we analyzed the loads in each link per cargo type and year. Next, we selected a subset of links from the initial network based on a minimum number of trains that would run in the links given the results of the network loading procedure. We carried out an all-or-nothing assignment once again to check the loading alterations in each link and, finally, we chose a set of nodes among those representing the microregions of Santa Catarina to locate the terminals considered in this paper, based on the major types of products that would flow through them. The steps of the proposed procedure are detailed as follows and their respective results are also presented.

Firstly, we built a triangulation connecting the virtual center points of the microregions of the state as previously explained, as shown in Figure 4. The sides of the polygons created by Delaunay triangulation are the railway links connecting the center points of the microregions. Some of them were assumed to be existing links from the current railway network, while others were assumed to be new, as shown in Figure 4. Note that these links were created connecting the state of Santa Catarina to other Brazilian states and also to the surrounding countries.

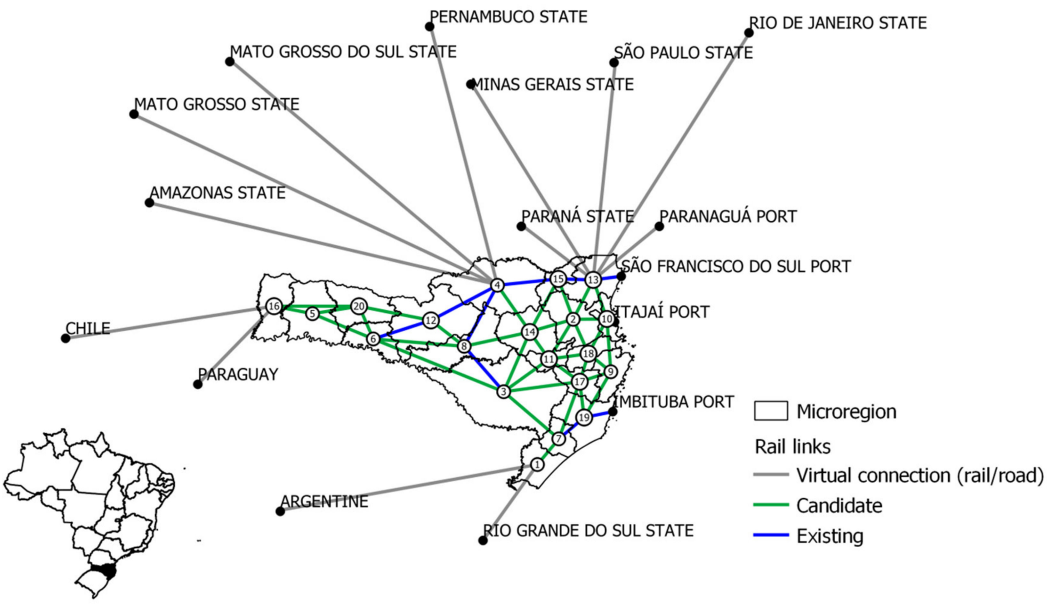

Figure 4. Existing and candidate links and nodes of the initial network.

Next, given the network of Figure 4, we considered the following set of products: those produced within Santa Catarina and transported to other locations in Brazil or other countries through its ports, those produced within the state and transported to other Brazilian states or surrounding countries by land, and those products coming from other locations to the microregions of Santa Catarina. Table 1 presents the tonnage of products flowing within the state in 2005 and 2015, and the expected values for 2023 provided by the Road Plan of the Department of Infrastructure of Santa Catarina [64]. We grouped the freight into four classes: bulk cargo (B), containerized cargo (C), refrigerated (R), and liquid (L). Table 2 summarizes the freight volume according to this classification.

Table 1. Freight volumes flowing within Santa Catarina per year (10^3 ton/year).

Product	2005	2015	2023	Class *
Sugar–Refined	157.56	176.99	192.77	C
Sugar–Raw	314.45	352.44	383.17	C
Rice	951.45	1087.35	1289.42	B
Beverages–Ingredients	429.01	510.63	700.20	C
Beverages–Final product	1223.27	1456.01	1996.55	C
Limestone	618.84	702.77	817.54	B
Meat	1982.43	2499.81	4484.17	R
Pottery	1467.24	1802.63	2840.42	C
Clay	931.40	1144.31	1803.09	B
Cement	1949.02	2301.45	3058.01	C
Mineral Coal	570.00	673.07	894.33	B
Clinker	406.63	480.16	638.00	B
Fuel–Outbound	3793.91	4280.48	4676.47	L
Fuel–Internal Distribution	1597.86	1790.89	1947.05	L
Soy Bean	3359.23	3791.93	4335.92	B
Petroleum Coke	504.20	595.37	791.09	B
Fertilizer	606.73	689.02	801.54	B
Cigarettes–Final Product	198.78	233.64	305.00	C
Tobacco	110.86	130.30	170.10	C
Apple	213.69	238.51	264.68	C
Wood	1615.04	1806.57	2016.14	C
Furniture	1080.51	1208.65	1348.86	C
Mechanical Industry–Final product	683.16	775.82	902.51	C
Mechanical Industry–Raw material	1093.67	1242.00	1444.83	C
Corn	2719.30	3069.57	3509.93	B
Corn–Inbound	2501.27	2823.46	3228.51	B
Paper and Cardboard–Final product	1376.57	1596.78	1987.35	C
Paper and Cardboard–Raw material	1895.30	2198.49	2736.24	C
Plastic–Final product	540.26	644.13	889.07	C
Plastic–Raw material	628.60	749.45	1034.44	C
Textile–Final product	221.21	256.95	321.39	C
Textile–Raw material	300.65	349.23	436.81	C
Wheat	615.50	687.00	762.37	B
Glass–Final product	226.00	281.49	474.03	C
Glass–Raw material	200.00	249.11	419.49	C
Total	37,083.60	42,876.45	53,901.53	-

* B = Bulk Cargo; C = Container; L = Liquid; R = Refrigerated.

Table 2. Summary of freight volumes per year and class (10^3 ton/year).

Class	2005	2015	2023
Bulk Cargo (B)	13,784.55	15,744.00	18,871.75
Container (C)	15,924.84	18,561.27	23,922.09
Liquid (L)	5391.77	6071.37	6623.52
Refrigerated (R)	1982.43	2499.81	4484.17
Total	37,083.60	42,876.45	53,901.53

Given the existing and expected tonnage of products flowing in the state of Santa Catarina, we applied an all-or-nothing assignment procedure to the network of Figure 4 connecting the microregions of Santa Catarina, and other states and countries. We considered that flows can be assigned to links in both directions between a pair of nodes, given the existing single line railway tracks and a set of new links connecting the microregions.

The assignment of the total freight presented in Table 1 per year and freight classes (bulk cargo, containerized, refrigerated, and liquid) resulted in link loads represented in Figure 5 per year and cargo type. We also assigned the overall freight per year. We did not consider a modal split since we assumed it would be equally applied to all the products and routes and, thus, in the same proportions of the total freight transported across the state. In each figure, consider that the thinner part of the link is the origin, from where it becomes thicker as it directs towards the destination.

Regarding the bulk cargo, most of the inbound flows come from the Brazilian states of Mato Grosso, Mato Grosso do Sul, Paraná in the North, and Rio Grande do Sul in the South, as it essentially flows outbound to the state of São Paulo, and internationally through the port of São Francisco do Sul. Note that the patterns remain almost the same through the years.

The containerized freight also comes mainly from Mato Grosso, Mato Grosso do Sul, Paraná, and Rio Grande do Sul, but flows out to the states of Minas Gerais, Paraná, São Paulo, Rio de Janeiro, and Rio Grande do Sul, while the international cargo is exported mainly through the port of Itajaí. Once again, the freight increases through time with the same patterns.

The state of Santa Catarina is well-known by its refrigerated cargo coming from the western microregions, mainly frozen meat. This is confirmed by the fact that any freight of this type comes from other states, and that the freight flows from the west to the ports through the northern links. This cargo is exported through the port of Itajaí in cooled containers to Minas Gerais, Paraná, São Paulo, Rio de Janeiro, and Rio Grande do Sul in Brazil. Note that the freight sent to São Paulo and Rio Grande do Sul increases more than those sent to the other states in 2023. Regarding liquid cargo, it comes mainly from Paraná, and in minor portion from Rio Grande do Sul, flowing from the coast to the other regions in the interior of Santa Catarina. Note that the volumes remain almost the same across the years.

When all the freight is assigned to the network connecting the microregions of Santa Catarina, the highest inbound volumes come from Mato Grosso do Sul (bulk cargo and containers), Paraná (bulk cargo, containers, and liquid cargo), and Rio Grande do Sul (bulk cargo and containers). The outbound volumes are mainly sent to Paraná and São Paulo (containers and refrigerated cargo). Within the state of Santa Catarina, the flows are mainly concentrated from west to east (bulk cargo, containers, and refrigerated), on the coast because of the ports (refrigerated and containers), and the liquid cargo flowing through the state. Note that the freight increases in the center of the state comparing the assignment of 2023 with 2005 and 2015.

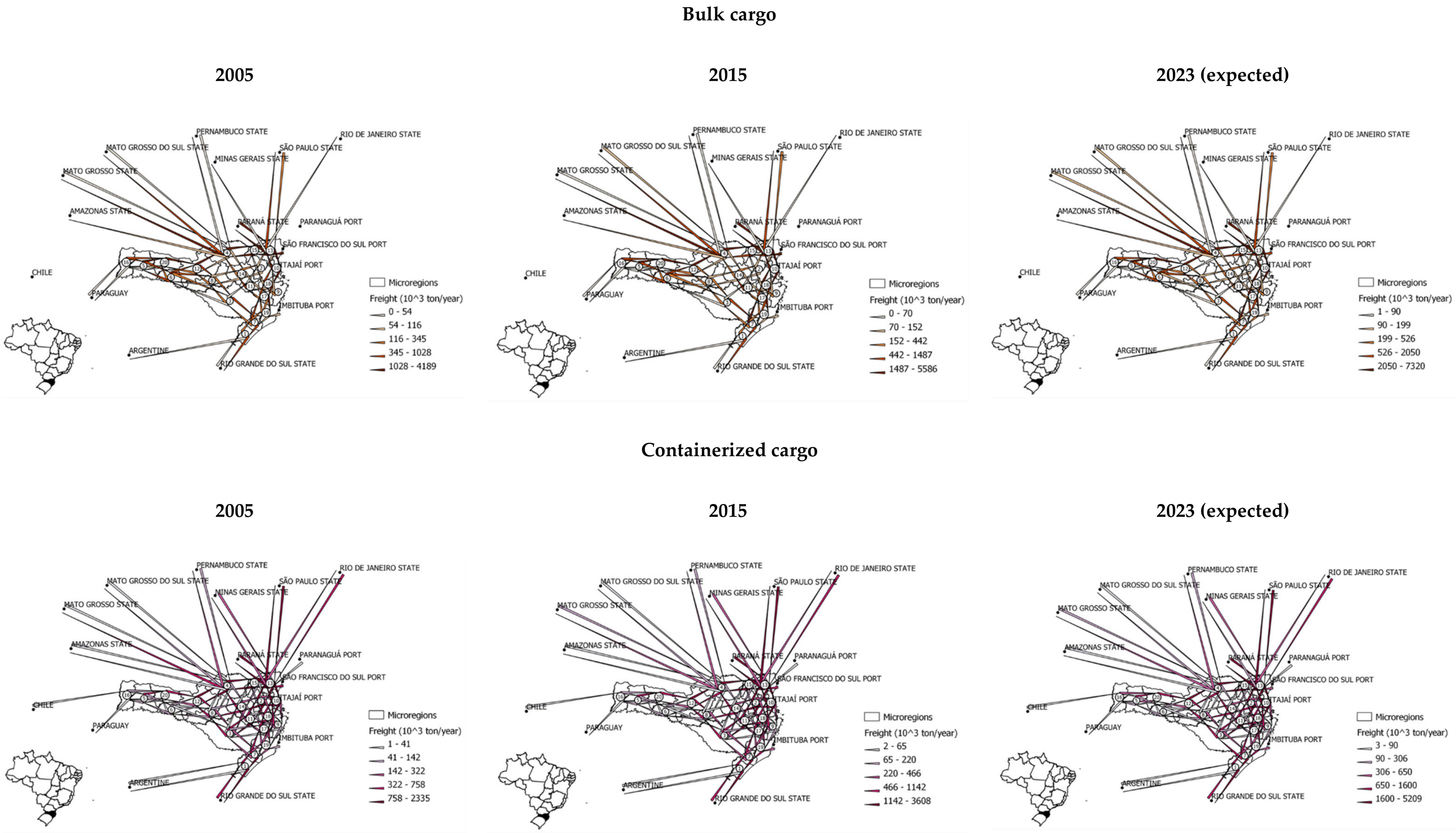

Figure 5. *Cont*.

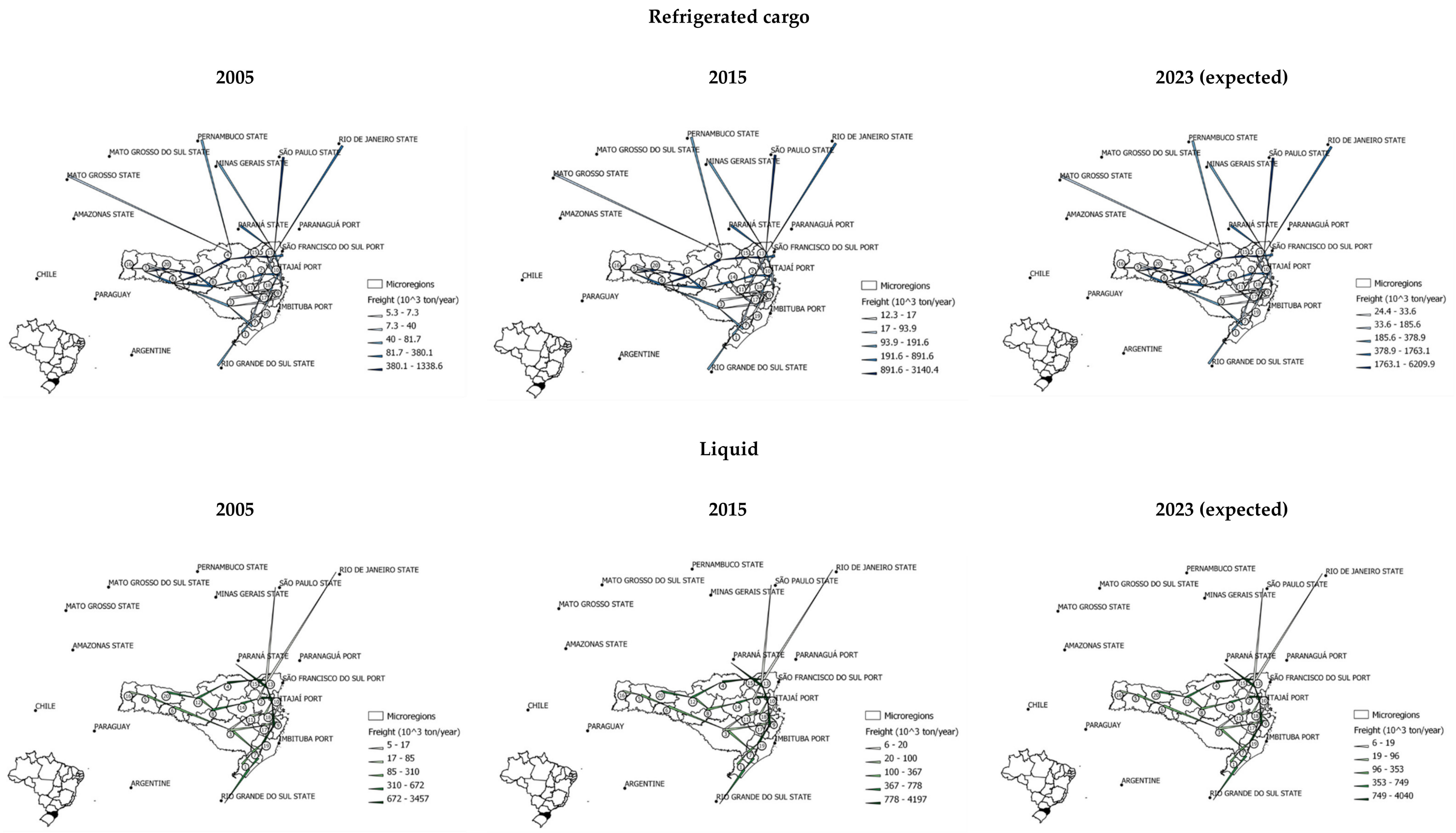

Figure 5. *Cont.*

Total

2005 **2015** **2023 (expected)**

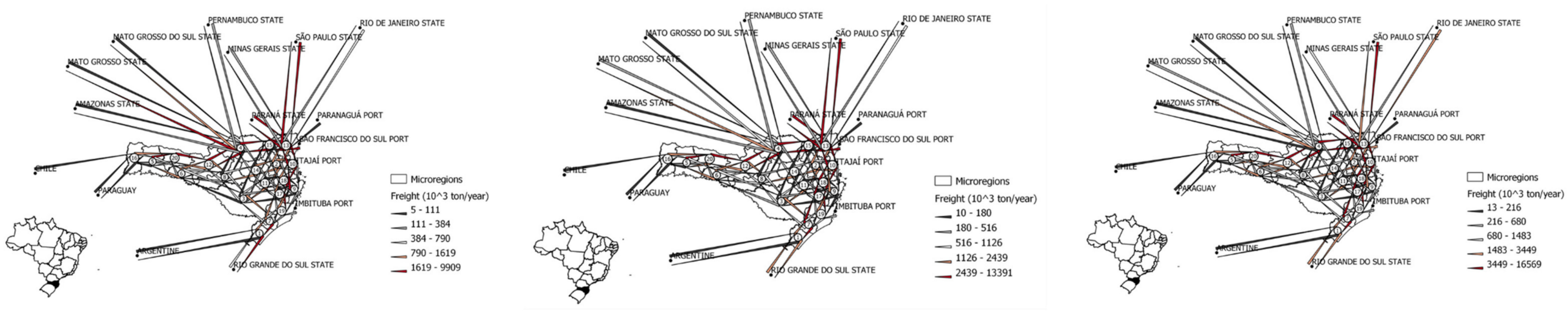

Figure 5. Freight transported between microregions of Santa Catarina per year and class.

The flow patterns in Figure 5 were considered to select the new links that would connect the microregions of Santa Catarina on a new railway network. To this end, we calculated the number of trains expected to run in each link of the network (in both directions) given the assignment of the total freight expected to be transported in 2023 considering standard trains with 20 mixed types of wagons of 80 ton each (i.e., minimum of 1600 ton per day in both directions of a link, or 584,000 ton per year).

Figure 6 shows the percentage of links where a given number of standard trains would run given the expected total freight loads in 2023. Note that the highest number of links would have between two and four daily trains running in both directions, 52% of the links would have three or less trains per day, and only 17% of the links would have between 12 and 40 trains running in both directions per day.

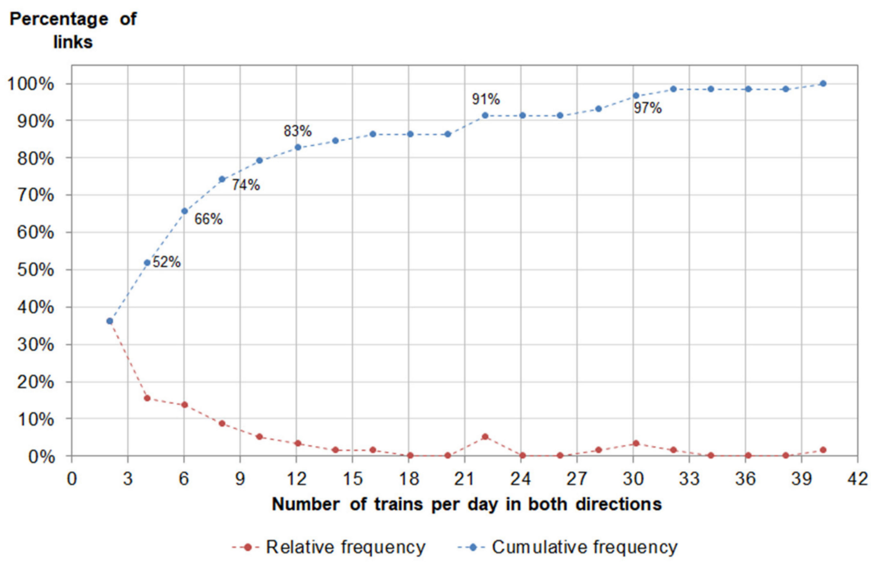

Figure 6. Percentage of links per estimated number of bidirectional trains running on them.

Given the assignment results and the percentage of links with a given number of standard trains running per day on them, we selected those links with at least six daily trains to be connected to the future network of the state of Santa Catarina. These selected links are shown in Figure 7 as a result of the proposed network expansion.

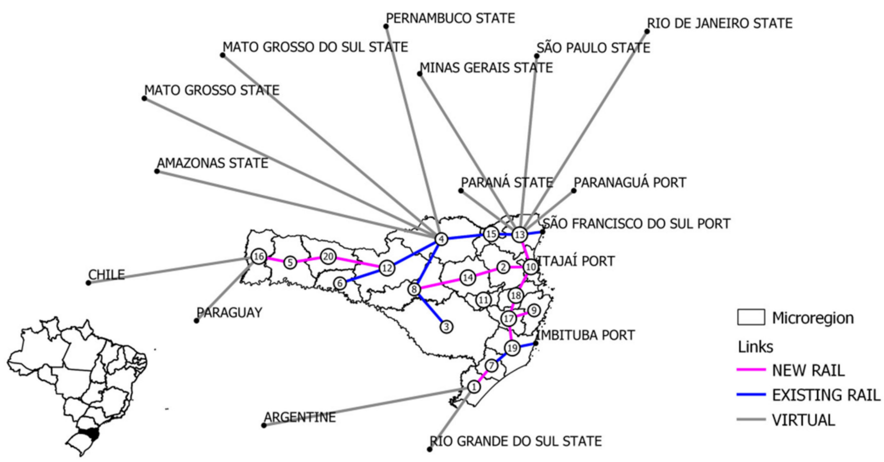

Figure 7. Proposed railway network for future freight transport.

In Figure 7, the geo-strategic railway network would be expanded to the west connecting the Microregions 5 (Chapecó), 16 (São Miguel do Oeste), and 20 (Xanxerê) to the existing network in Microregion 12 (Joaçaba). The center of the state would be connected in Nodes 2 (Blumenau) and 14 (Rio do Sul), while new links on the coast integrate the existing network. It is important to highlight that the nodes of the network would not necessarily be located in the center point of each microregion as depicted in Figure 7, as it is a merely representation of these administrative areas. Note that only Microregion 11 (Ituporanga) would not be connected to the proposed railway network as it does not meet the link selection criteria. However, it would benefit from the cargo coming to Microregion 3 (Campos de Lages), and flowing through Nodes 17 (Tabuleiro) and 18 (Tijucas).

In order to analyze the impacts of the proposed network, we assigned the freight presented in Table 1 to the geo-strategic network shown in Figure 7 by cargo type, and the overall freight to be transported in 2023, resulting in Figure 8.

Given the assignments of freight per cargo type, Figure 8 shows that the bulk cargo coming from Mato Grosso, Mato Grosso do Sul, Paraná, and Rio Grande do Sul still flows through the state, mainly in the north and east. Figure 8 illustrates that the containerized cargo flows mainly on the coast of Santa Catarina, and to the states of Paraná, São Paulo, Rio de Janeiro, and Rio Grande do Sul. It also shows that the refrigerated cargo from the west flows to the coast, to be exported from the Itajaí Port and transported to the states of Minas Gerais, Paraná, São Paulo, Rio de Janeiro, and Rio Grande do Sul in Brazil. The liquid cargo comes mainly from Paraná and Rio Grande do Sul and is transported to the microregions of Santa Catarina. Finally, Figure 8 shows that the majority of freight is transported from the west to the east, and across the coast from where it is exported and sent to the other Brazilian states, mainly Paraná and São Paulo.

The obtained results show that most of the freight to be transported in 2023 is supposed to flow between the microregions from the northwest to the northeast, through the existing railway links and the planned network. Note that the existing railway to the south of the state is not considerably used in the future. This is because the system is highly specific and nowadays used to transport minerals from the extreme south to the port. The next section presents the location of specialized terminals to be operated at specific nodes of the new proposed network.

4.3. Location of Specialized Terminals for Freight Transport

In order to implement the rail freight corridors in the state of Santa Catarina, a set of intermodal terminals are supposed to be operated in order to enable the load exchange between trains and trucks, as the distances to be covered within the state are relatively small (less than 550 km from west to east and 400 km from north to south), and advantages can be taken from the intermodality. While the transhipment terminals can add high operating costs to the railway, technological alternatives can be considered in order to minimize its effects, such as the CarConTrain (CCT) [65] at feeders and small terminals, with completely automated equipment that require small areas.

Some specific infrastructure must be considered at the terminals depending on its region and types of freight flowing through them. Whilst a wide range of grains are produced in the west of Santa Catarina, this region would benefit from a structure prepared for a safe and efficient transition of bulk cargo from trucks coming from the fields to the trains heading to ports or other regions of the country. On the other hand, containers are used for general cargo and cooled food products. Nowadays, they are taken directly from their production location to their final destination. However, when considering new terminals to handle these containers, a storage area must be reserved and equipped with a set of specialized equipment: Reach Stackers, forklifts to move the containers across the area; Transteiners, fixed and large structures to enable transhipment between trucks and trains; and energy sockets to receive cooled containers. There are also very specific situations, such as the transportation of large generators, military vehicles, and trucks, which require more specific technologies usually embedded in the wagons.

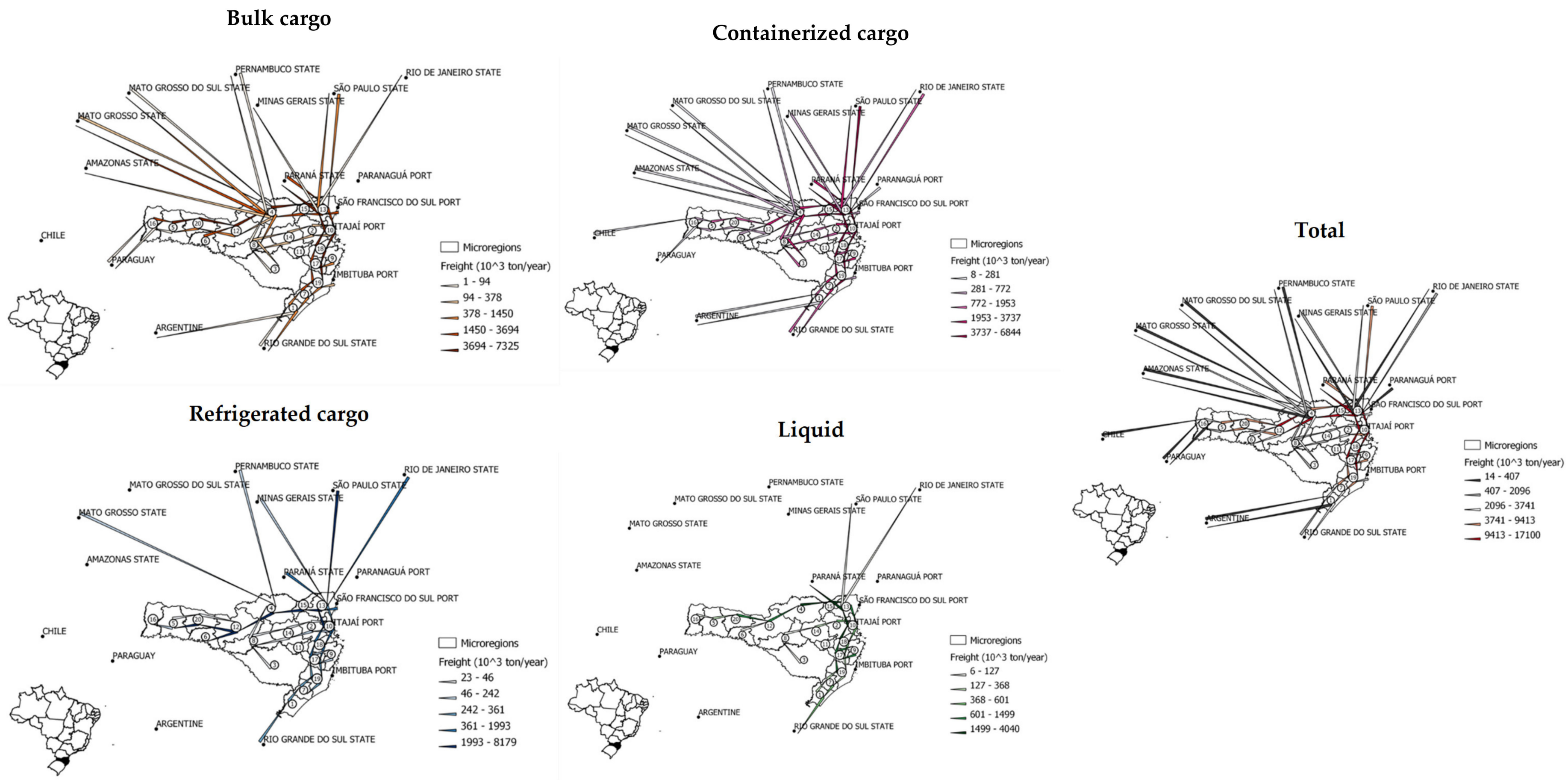

Figure 8. Expected flows to be transported in 2023.

The choice location of each type of terminal in the network previously proposed was based on the analysis of the existing road and railway infrastructure, and also the new lines shown in Figure 7. The type of terminal was chosen as a function of the number of railway links in the microregion, their total flows, the types of products flowing through it, and their geographic location. The Feeder (FD) was located in microregions at the terminal links of the network, connecting it to the existing and planned road network, as shown in Figure 3. A Small Terminal (ST) was set into microregions with at least two railway links connected to the node, where specific installations are supposed to be built for cargo loading and storage, depending on the type of freight (storehouses for bulk cargo and/or specific yards for conventional or cooled containers). The CHFS was considered to be introduced in microregions with more than two railway links connected to freeway road links. Figure 9 shows the proposed network for future operation of freight trains in Santa Catarina with the types of terminals established according to these rules.

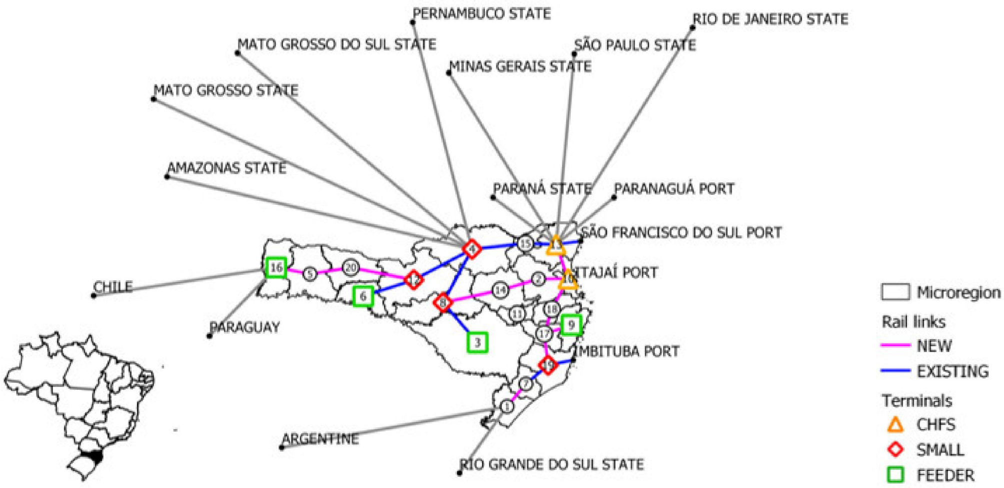

Figure 9. New railway network and location of the specialized terminals.

The intermodal terminals have been located according to their definitions. The feeders have been located in the extreme links of the network, in Nodes 1 (Araranguá), 3 (Campos de Lages), 6 (Concórdia), 9 (Florianópolis), and 16 (São Miguel do Oeste). The microregions of Chapecó (Node 5) and Xanxerê (Node 20) can be served either by Feeder 6 or 16, while the microregion of Rio do Sul (Node 14) and Blumenau (Node 2) can be served by Campos de Lages, and the microregion of Criciúma (Node 7) can be served by the feeder in Araranguá. The feeder in Florianópolis (Node 9) was included as it will serve the capital of the state, the second most populated region of Santa Catarina, and the surrounding microregions of Tabuleiro and Tijucas (Nodes 17 and 18, respectively).

The small terminals have been proposed to be installed in Microregions 4 (Canoinhas), 8 (Curitibanos), 12 (Joaçaba), and 19 (Tubarão). These terminals are mostly concentrated in the north of Santa Catarina, as they are microregions which receive cargo coming from the west (mainly refrigerated) and from the other states in the north (mainly bulk cargo). Note that node Canoinhas can be used as an intermodal feeder to the microregion at Node 15 (São Bento do Sul). Joaçaba has been selected to receive a small terminal as it moves freight from the north and east (liquid) and from the center of the state to the east (bulk cargo and containers).

Finally, two Container Hub-Feeder Services (CHFS) have been proposed to be located in Microregions 10 (Itajaí) and 13 (Joinville). The first intermodal terminal receives containerized and refrigerated cargo from the west and central part of the state, while the second is responsible for moving bulk cargo from the center of Santa Catarina, and also from other states. Both intermodal terminals are also capable of distributing liquid cargo from the other states to the microregions of Santa Catarina. It is important to highlight that these terminals are located in the most populated portions of the state.

5. Conclusions

A geo-strategic railway network for freight services is proposed in this paper, designed with the purpose of meeting the future needs of freight transport in the state of Santa Catarina, South Brazil. We analyzed the current and future freight flows over a proposed geo-strategic rail network composed of existing links and a new set of connections. Specialized intermodal terminals were located at some nodes of the newly designed network considering the four types of cargo (bulk, containerized, refrigerated, and liquid).

The inbound freight from other Brazilian states and the outbound cargo flows were assigned to a fully connected network and the most relevant links were selected. The evaluation of the flows by freight type resulted in the location of three types of intermodal terminals (Feeders, Small Terminals, and Container Hub-Feeder Services) based on the incoming and outgoing flows in Santa Catarina.

The study showed that the multimodal connectivity should be considered for identifying new links and terminals to handle increasing demands and multi-type freight flows. Location and technological specifications of terminal operations are crucial in handling seamlessly multiple freight types because a few nodes of the geo-strategic railway network would not necessarily create a need for a specialized terminal, instead they might well work with specialized terminals located in other near regions.

Despite the small geographical area of Santa Catarina compared to the country, future studies would include the development and application of modal split models, and the freight flow patterns obtained by other network configurations and their evolution over time. Moreover, in future research, the analysis developed in this paper can be used to examine a larger network by including smaller regions or at a city level, or by applying network design optimization models that can deal with more complex link combinations. In this sense, a cost and benefit analysis would be appropriate to assess the effects of including/excluding particular sections of the network, for example, on a cost benefit analysis framework over a strategic time horizon. In this case, a detailed evaluation of the infrastructure construction and maintenance costs, and the operational costs based on train timetables over time, would be required, and also the estimation of the benefits directly associated to the suppliers, the railway operators, and the wider social and economic benefits.

The dynamics of freight markets pose challenges for research because of commercial imbalances among the stakeholders involved, and the assumptions of simple market growth over time that depends on large-scale construction capabilities, planning policies, and economic and political stability. The obtained results, however, are suggestive of the possible trends of planning strategies, which would be investigated using network topological indicators.

Our approach can also be extended to encompass development of a joint passenger and freight geo-strategic rail network, which would produce useful results for both decision makers and industry. In this respect, economic analysis considering construction and operating costs can be analyzed, including wider economic benefits and externalities, such as energy consumption and environmental impacts.

Author Contributions: C.A.I., Y.A. and M.M. conceived and designed the experiments; C.A.I. performed the experiments; C.A.I. and M.M. analyzed the data; C.A.I., Y.A. and M.M. wrote the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by FAPESC and CONFAP—The UK Academies—Newton Fund grant number: 2016TR411.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Vasconcellos, E.A. Urban transport policies in Brazil: The creation of a discriminatory mobility system. *J. Transp. Geogr.* **2018**, *67*, 85–91. [CrossRef]

2. Fontoura, W.B.; Chaves, G.D.L.D.; Ribeiro, G.M. The Brazilian urban mobility policy: The impact in São Paulo transport system using system dynamics. *Transp. Policy* **2019**, *73*, 51–61. [CrossRef]
3. De Miranda, R.M.; Perez-Martinez, P.J.; Andrade, M.D.F.; Ribeiro, F.N.D. Relationship between black carbon (BC) and heavy traffic in São Paulo, Brazil. *Transp. Res. Part D: Transp. Environ.* **2019**, *68*, 84–98. [CrossRef]
4. Paiva, K.M.; Cardoso MR, A.; Zannin PH, T. Exposure to road traffic noise: Annoyance, perception and associated factors among Brazil's adult population. *Sci. Total Environ.* **2019**, *650*, 978–986. [CrossRef] [PubMed]
5. Rodrigues, N.; Losekann, L.; Silveira Filho, G. Demand of automotive fuels in Brazil: Underlying energy demand trend and asymmetric price response. *Energy Econ.* **2018**, *74*, 644–655. [CrossRef]
6. Islam, D.M.Z.; Blinge, M. The future of European rail freight transport and logistics. *Eur. Transp. Res. Rev.* **2017**, *9*. [CrossRef]
7. Branco, J.E.H.; Bartholomeu, D.B.; Junior, P.N.A.; Caixeta Filho, J.V. Evaluation of the economic and environmental impacts from the addition of new railways to the Brazilian's transportation network: An application of a network equilibrium model. *Transp. Policy* **2020**. [CrossRef]
8. Wang, J.J.; Yau, S. Case studies on transport infrastructure projects in belt and road initiative: An actor network theory perspective. *J. Transp. Geogr.* **2018**, *71*, 213–223. [CrossRef]
9. Marinov, M.; Şahin, I.; Ricci, S.; Vasic-Franklin, G. Railway operations, time-tabling and control. *Res. Transp. Econ.* **2013**, *41*, 59–75. [CrossRef]
10. Li, L.; Negenborn, R.R.; De Schutter, B. Intermodal freight transport planning—A receding horizon control approach. *Transp. Res. Part C Emerg. Technol.* **2015**, *60*, 77–95. [CrossRef]
11. Di Febbraro, A.; Sacco, N.; Saeednia, M. An agent-based framework for cooperative planning of intermodal freight transport chains. *Transp. Res. Part C: Emerg. Technol.* **2016**, *64*, 72–85. [CrossRef]
12. Wang, H.; Han, J.; Su, M.; Wan, S.; Zhang, Z. The relationship between freight transport and economic development: A case study of China. *Res. Transp. Econ.* **2020**, 100885. [CrossRef]
13. Tapia, R.J.; De Jong, G.; Larranaga, A.M.; Cybis, H.B.B. Application of MDCEV to infrastructure planning in regional freight transport. *Transp. Res. Part A Policy Pract.* **2020**, *133*, 255–271. [CrossRef]
14. Kumar, A.; Ramesh, A. Location selection of multimodal freight terminal under STEEP sustainability. *Res. Transp. Bus. Manag.* **2019**, *33*, 100434. [CrossRef]
15. SteadieSeifi, M.M.; Dellaert, N.N.; Nuijten, W.W.; Van Woensel, T.T.; Raoufi, R.R. Multimodal freight transportation planning: A literature review. *Eur. J. Oper. Res.* **2014**, *233*, 1–15. [CrossRef]
16. Bergqvist, R. Evaluating road–rail intermodal transport services—A heuristic approach. *Int. J. Logist. Res. Appl.* **2008**, *11*, 179–199. [CrossRef]
17. Protic, S.M.; Geerlings, H.; van Duin, R. Environmental Sustainability of Freight Transportation Terminals. In *Sustainable Transportation and Smart Logistics*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 233–260.
18. Arnold, P.; Peeters, D.; Thomas, I. Modelling a rail/road intermodal transportation system. *Transp. Res. Part E: Logist. Transp. Rev.* **2004**, *40*, 255–270. [CrossRef]
19. Elevli, B. Logistics freight center locations decision by using Fuzzy-PROMETHEE. *Transport* **2014**, *29*, 412–418. [CrossRef]
20. Awasthi, A.; Chauhan, S.S.; Goyal, S.K. A multi-criteria decision making approach for location planning for urban distribution centers under uncertainty. *Math. Comput. Model.* **2011**, *53*, 98–109. [CrossRef]
21. Marinov, M.V.; Viegas, J.M. Tactical management of rail freight transportation services: Evaluation of yard performance. *Transp. Plan. Technol.* **2011**, *34*, 363–387. [CrossRef]
22. Marinov, M.; Woroniuk, C.; Zunder, T.H. Recent developments with Single Wagon Load services, policy and practice in Europe. In Proceedings of the 2012 Federated Conference on Computer Science and Information Systems (FedCSIS 2012), Wroclaw, Poland, 9–12 September 2012; pp. 1097–1104.
23. Woroniuk, C.; Marinov, M.; Zunder, T.; Mortimer, P.; Zunder, T.H. Time series analysis of rail freight services by the private sector in Europe. *Transp. Policy* **2013**, *25*, 81–93. [CrossRef]
24. Fernández, L.E.; De Cea Ch, J.; Giesen, E.R. A strategic model of freight operations for rail transportation systems. *Transp. Plan. Tech.* **2004**, *27*, 231–260.
25. Powell, W.; Topaloglu, H. *Fleet Management*; Princeton University: Princeton, NJ, USA, 2002.
26. Powell, W.; Carvalho, C.; Simao, H.; Godfrey, G. *Dynamic Fleet Management as a Logistics Queuing Network*; Statistics and Operations Research, Technical Report SOR-94-18; Princeton University: Princeton, NJ, USA, 1995.
27. Powell, W.; Shapiro, J.; Simao, H. *Dynamic Management of Heterogeneous Resources*; Statistics and Operations Research, Technical Report SOR-98-06; Princeton University: Princeton, NJ, USA, 1998.
28. Lin, B.; Liu, C.; Wang, H.; Lin, R. Modeling the railway network design problem: A novel approach to considering carbon emissions reduction. *Transp. Res. Part D: Transp. Environ.* **2017**, *56*, 95–109. [CrossRef]
29. Rosell, F.; Codina, E. A model that assesses proposals for infrastructure improvement and capacity expansion on a mixed railway network. *Transp. Res. Procedia* **2020**, *47*, 441–448. [CrossRef]
30. Ortúzar, J.D.; Willumsen, L.G. *Modelling Transport*; John Wiley & Sons: Chichester, UK, 2011.
31. Ferrari, P. The dynamics of modal split for freight transport. *Transp. Res. Part E: Logist. Transp. Rev.* **2014**, *70*, 163–176. [CrossRef]
32. Jacyna-Gołda, I.; Żak, J.; Gołębiowski, P. Models of traffic flow distribution for various scenarios of the development of proecological transport system. *Arch. Transp.* **2014**, *32*, 17–28. [CrossRef]

33. Crainic, T.G. Service network design in freight transportation. *Eur. J. Oper. Res.* **2000**, *122*, 272–288. [CrossRef]
34. Crainic, T.G.; Roy, J. OR tools for tactical freight transportation planning. *Eur. J. Oper. Res.* **1988**, *33*, 290–297. [CrossRef]
35. Crainic, T.G.; Laporte, G. Planning models for freight transportation. *Eur. J. Oper. Res.* **1997**, *97*, 409–438. [CrossRef]
36. Crainic, T.; Ferland, J.-A.; Rousseau, J.-M. A Tactical Planning Model for Rail Freight Transportation. *Transp. Sci.* **1984**, *18*, 165–184. [CrossRef]
37. Crainic, T. A Survey of optimization models for long-haul freight transportation. In *Handbook of Transportation Science*, 2nd ed.; Kluwer: Amsterdam, The Netherlands, 2002.
38. Farvolden, J.M.; Powell, W.B. Subgradient Methods for the Service Network Design Problem. *Transp. Sci.* **1994**, *28*, 256–272. [CrossRef]
39. Labbe, M.; Peeters, D.; Thisse, J. Location on Networks. In *Handbooks in Operations Research and Management Science*; Elsevier: Amsterdam, The Netherlands, 1995.
40. Duan, L.; Tavasszy, L.; Peng, Q. Freight network design with heterogeneous values of time. *Transp. Res. Procedia* **2017**, *25*, 1144–1150. [CrossRef]
41. Alumur, S.; Kara, B.Y. Network hub location problems: The state of the art. *Eur. J. Oper. Res.* **2008**, *190*, 1–21. [CrossRef]
42. Campbell, J.F.; O'Kelly, M.E. Twenty-Five Years of Hub Location Research. *Transp. Sci.* **2012**, *46*, 153–169. [CrossRef]
43. Yang, H.; Huang, H.-J. The multi-class, multi-criteria traffic network equilibrium and systems optimum problem. *Transp. Res. Part B Methodol.* **2004**, *38*, 1–15. [CrossRef]
44. Cantos-Sánchez, P.; Moner-Colonques, R.; Sempere-Monerris, J.J.; Álvarez-SanJaime, Ó. Viability of new road infrastructure with heterogeneous users. *Transp. Res. Part A Policy Pr.* **2011**, *45*, 435–450.
45. Tan, Z.; Yang, H. The impact of user heterogeneity on road franchising. *Transp. Res. Part E Logist. Transp. Rev.* **2012**, *48*, 958–975. [CrossRef]
46. Wang, J.Y.T.; Ehrgott, M. Modelling Route Choice Behaviour in a Tolled Road Network with a Time Surplus Maximisation Bi-objective User Equilibrium Model. *Procedia Soc. Behav. Sci.* **2013**, *80*, 266–288. [CrossRef]
47. Zhao, Y.; Kockelman, K.M. On-line marginal-cost pricing across networks: Incorporating heterogeneous users and stochastic equilibria. *Transp. Res. Part B Methodol.* **2006**, *40*, 424–435. [CrossRef]
48. Duan, L.; Tavasszy, L.A.; Rezaei, J. Freight service network design with heterogeneous preferences for transport time and reliability. *Transp. Res. Part E Logist. Transp. Rev.* **2019**, *124*, 1–12. [CrossRef]
49. Yamada, T.; Imai, K.; Nakamura, T.; Taniguchi, E. A supply chain-transport supernetwork equilibrium model with the behaviour of freight carriers. *Transp. Res. Part E: Logist. Transp. Rev.* **2011**, *47*, 887–907. [CrossRef]
50. Bell, M.G.; Liu, X.; Rioult, J.; Angeloudis, P. A cost-based maritime container assignment model. *Transp. Res. Part B Methodol.* **2013**, *58*, 58–70. [CrossRef]
51. Sheffi, Y. *Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods*; Prentice-Hall: Englewood Cliffs, NJ, USA, 1985.
52. Marinov, M.; Viegas, J.M. A mesoscopic simulation modelling methodology for analyzing and evaluating freight train operations in a rail network. *Simul. Model. Pr. Theory* **2011**, *19*, 516–539. [CrossRef]
53. Kuby, M.; Xu, Z.; Xie, X. Railway network design with multiple project stages and time sequencing. *J. Geogr. Syst.* **2001**, *3*, 25–47. [CrossRef]
54. Horner, M.W.; Grubesic, T.H. A GIS-based planning approach to locating urban rail terminals. *Transportation* **2001**, *28*, 55–77. [CrossRef]
55. De Luca, M.; Dell'Acqua, G.; Lamberti, R. High-Speed Rail Track Design Using GIS And Multi-Criteria Analysis. *Procedia Soc. Behav. Sci.* **2012**, *54*, 608–617. [CrossRef]
56. Ngunyi, J.; Mundia, C.; Gachari, M. Analysis of Standard Gauge Railway Using GIS and Remote Sensing. *Am. J. Geogr. Inf. Syst.* **2017**, *6*, 54–63.
57. Kurwi, S.; Demian, P.; Hassan, T.M. Integrating BIM and GIS in railway projects: A critical review. In Proceedings of the 33rd Annual ARCOM Conference, Cambridge, UK, 4–6 September 2017; pp. 45–53.
58. Marinov, M.; Zunder, T.; Islam, D. Concepts, models and methods for rail freight and logistics performances: An inception paper. In Proceedings of the 12th World Conference on Transport Research, Lisbon, Portugal, 11–15 July 2010.
59. Palmer, A.; Mortimer, P.; Greening, P.; Piecyk, M.; Dadhich, P. A cost and CO_2 comparison of using trains and higher capacity trucks when UK FMCG companies collaborate. *Transp. Res. Part D Transp. Environ.* **2018**, *58*, 94–107. [CrossRef]
60. Kordnejad, B. Stakeholder analysis in intermodal urban freight transport. In Proceedings of the 9th International Conference on City Logistics, Tenerife, Spain, 17–19 June 2015; Volume 12, pp. 750–764.
61. IBGE. Contagem da População 2007. Instituto Brasileiro de Geografia e Estatística. 2019. Available online: https://www.ibge.gov.br/estatisticas/downloads-estatisticas.html (accessed on 21 August 2020).
62. IBGE. Divisão do Brasil em Mesorregiões e Microrregiões. Instituto Brasileiro de Geografia e Estatística. 1990. Available online: https://biblioteca.ibge.gov.br/visualizacao/monografias/GEBIS%20-%20RJ/DRB/Divisao%20regional_v01.pdf (accessed on 21 August 2020).
63. Cignoni, P.; Montani, C.; Scopigno, R. DeWall: A fast divide and conquer Delaunay triangulation algorithm in Ed. *Comput. Des.* **1998**, *30*, 333–341. [CrossRef]

64. SIE Plano Diretor Rodoviário do Estado de Santa Catarina. Secretaria de Estado da Infraestrutura e Mobilidade de Santa Catarina. 2019. Available online: https://www.sie.sc.gov.br (accessed on 28 October 2019).
65. Kordnejad, B. Intermodal transport cost model and intermodal distribution in urban freight. *Procedia Soc. Behav. Sci.* **2014**, *125*, 358–372. [CrossRef]