

University of São Paulo
“Luiz de Queiroz” College of Agriculture

Improvements in the Brazilian agricultural products logistic network using a railway design method and a GIS-based optimization model

Connie Tenin Su

Thesis presented to obtain the degree of Doctor in
Science. Area: Applied Economics

Piracicaba
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RESUMO

Melhorias na rede logística de produtos agrícolas no Brasil usando um método de desenho de rede ferroviária e um modelo de otimização integrado ao SIG

O Brasil é um país de dimensões continentais, sendo comum transportar produtos por distâncias superiores a 2.000 km. Historicamente, o transporte de cargas é fortemente baseado no modo rodoviário, apesar de este não ser o modo mais econômico e ambientalmente eficiente para longas distâncias. Nos últimos anos, o governo brasileiro tem focado numa matriz de transportes mais equilibrada e racional, com vários projetos planejados para ligar áreas de alta produção a portos de exportação e poucos projetos voltados para o mercado interno. Como resultado, a matriz de transportes do Brasil para os mercados de exportação é mais balanceada, enquanto o transporte de cargas para o mercado doméstico é realizado quase que exclusivamente por rodovias. Este é um cenário adverso para as indústrias brasileiras que dependem de matérias primas produzidas em outras regiões do país, como o setor de aves e suínos dos estados de Santa Catarina e do Rio Grande do Sul. Esses estados do Sul precisam adquirir milho principalmente dos estados do Centro-Oeste, percorrendo rodovias por distâncias que facilmente superam 1.000 km, já que atualmente não há ferrovias ligando esses estados. A maior demanda ocorre em meses em que o valor dos fretes é maior e a disponibilidade de caminhões é menor, o que poderia ser amenizado utilizando-se uma estratégia de armazenagem; no entanto, estes estados sofrem de déficit de capacidade estática. Dessa forma, este trabalho busca traçar alternativas visando a melhoria da rede logística brasileira para o mercado doméstico de produtos agrícolas de forma mais sustentável, a partir da estruturação de um modelo de otimização em dois níveis de redes de transportes e de armazenagem, integrado com um Sistema de Informações Geográficas (SIG). O método proposto desenha uma nova ferrovia para conectar as regiões Centro-Oeste e Sul, seleciona armazéns e determina o volume de aumento da capacidade estática; avalia as infraestruturas de transporte mais utilizadas; e encontra os pontos de entrada mais promissores para importação de milho do Paraguai, da Argentina e de outros países. A função objetivo desenvolvida deu conta da minimização do custo total e das emissões de CO₂. Além disso, este trabalho propôs um método para desenhar uma nova ferrovia, que inclui critérios para definir a localização dos seus pontos de origem, intermediários e de destino e determinar a área de influência e carga potencial. A nova ferrovia proposta gerou resultados positivos, atraindo volume de carga considerável e gerando uma matriz de transportes mais balanceada e racional. Os efeitos positivos aumentaram quando a nova ferrovia foi combinada ao aumento ótimo na capacidade estática de armazenagem dos armazéns de grãos sólidos. Além disso, foi possível comparar a matriz de transportes melhorada com as de outros países de tamanho similar. Os resultados obtidos podem subsidiar os formuladores de política e os projetistas de ferrovia e reforçam a necessidade de múltiplas e coordenadas ações e medidas, além da importância de uma estratégia de planejamento de longo prazo.

Palavras-chave: Desenho de rede ferroviária, Otimização, Sistema de informações geográficas, Emissão de CO₂, Armazenamento de grãos, Matriz de transportes

ABSTRACT

Improvements in the Brazilian agricultural products logistic network using a railway design method and a GIS-based optimization model

Brazil is a country of continental dimensions, so it is very frequent the need to transport products through distances of over 2,000 km. Historically, freight transportation is heavily based on road mode, although it is not the most economical and environmentally efficient mode for long distances. In the past few years, the Brazilian government has focused on a more balanced and rational transportation matrix, with several planned projects aimed at linking high production areas to exporting ports and not many projects directed to the domestic market. As a result, Brazil's transportation matrix for export markets is more balanced, while freight transportation to the domestic market is done almost exclusively by road. This is an adverse scenario for Brazilian industries that depend on raw materials produced in other regions of the country, such as the poultry and pork sectors in the states of Santa Catarina and Rio Grande do Sul. These Southern states must procure maize especially from the Center-West states, traversing by road distances that can easily reach more than 1,000 km, as currently there is no railway linking these states. The higher demand occurs in months with higher freight values and lower truck availability, which could be alleviated by using a storage strategy; however, these states face a deficit of static storage capacity. Hence, this thesis aims to design alternatives for the improvement of the Brazilian logistics network related to domestic market of agricultural products in a more sustainable way, by proposing a two-level optimization model for transportation and warehouse networks, integrated with a Geographic Information System (GIS). The proposed method designs a new railway to link the Center-West and the South regions; selects the location of warehouses that need to increase the static storage capacity and determines the necessary volume for them; assesses the most used transportation infrastructures; and finds the most promising entry points to import maize from Paraguay, Argentina, and other countries. The objective function that was developed took into consideration the minimization of the total cost and the CO₂ emissions. In addition, this thesis proposed a railway network design model to project a new railway that includes the criteria to define its start, intermediate, and end points and to determine the area of influence and the potential cargo. The proposed new railway generated positive results, attracting substantial cargo volume and generating a more balanced and rational transportation matrix. The positive effects increased when the new railway was combined with the optimal increase of the static storage capacity of the bulk warehouses. In addition, it was possible to compare the improved Brazilian transportation matrix with the ones from other countries of similar size. The obtained results can subsidize policy makers and railway designers and reinforce the need of multiple and coordinated actions and measures, and the importance of a long-term planning strategy.

Keywords: Railway network design, Optimization, Geographic information system, CO₂ emissions, Grains storage, Transportation matrix

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LIST OF ACRONYMS

ACO	Ant Colony Optimization
AHP	Analytic Hierarchy Process
CO ₂	Carbon dioxide
FATO	Authorized Transportation Railway Olacyr de Moraes (<i>Ferrovia Autorizada de Transporte Olacyr de Moares</i>)
FCA	Center-Atlantic Railway (<i>Ferrovia Centro-Atlântica</i>)
FICO	Center-West Integration Railway (<i>Ferrovia de Integração Centro-Oeste</i>)
FIOL	West-East Integration Railway (<i>Ferrovia de Integração Oeste-Leste</i>)
FNS	North-South Railway (<i>Ferrovia Norte-Sul</i>)
GA	Genetic Algorithm
GDP	Gross Domestic Product
GHG	Greenhouse gas
GIS	Geographic Information Systems
ICMS	Tax on the Circulation of Goods and Services (<i>Imposto sobre Circulação de Mercadorias e Prestação de Serviços</i>)
O-D	Origin-Destination
NTN	New Northeastern Railway (<i>Ferrovia Nova Transnordestina</i>)
PNL	National Logistics Plan (<i>Plano Nacional de Logística</i>)
TKM	Tonne-kilometer
TKU	Net tonne-kilometer (<i>Tonelada-Quilômetro Útil</i>)
VKU	Net value-kilometer (<i>Valor-Quilômetro Útil</i>)

1. INTRODUCTION

Brazil is a country of continental dimensions. Due to climate and historical background differences, each region is specialized on the production of certain products, resulting in goods traveling throughout the country to reach consumer markets. In recent years, the shift of grains production to the Center-West region has considerably increased the distance between important production areas and exporting ports (United States International Trade Commission, 2012), as well as to the domestic market. Thus, in most of times it is necessary to transport products across the country traveling distances over 2,000 km, resulting in an unbalanced flow of cargos between regions. Historically, freight transportation is heavily based on road mode (64.9%, as of 2021 in TKU¹), followed by rail (15.0%), cabotage/coastal shipping (10.5%), waterways (5.3%), pipelines (4.5%), and air (0.03%) (CNT, 2022; de Valois et al., 2011; Gouvea and Montoya, 2014; Plaza et al., 2020). If the transportation of iron ore - which is done predominantly by rail - is excluded from the analysis, the participation of road mode is even higher (Ministério dos Transportes, 2012).

However, road transportation is not the most efficient mode for long distances, considering its low energy efficiency and high socioeconomic and environmental costs, such as the use of carbon-intensive fuel. Brazil also suffers from lack of intermodal integration, low quality in logistics infrastructure (e.g., highways, ports, airports, and water transportation systems), limited storage capacity (especially for agricultural products), and high insurance costs (due to higher levels of risk of loss) that affect the flow of products. This scenario reflects negatively in Brazil's competitiveness with other countries. For instance, the United States has a comparable size and competes with Brazil for maize and soybean's export markets. In contrast, the United States' transportation matrix is more balanced, with a higher share of railways (27%, as of 2019 in TKU), pipelines (22%), inland waterways (5%) and cabotage (3%) than road (43%), which reflects on differences in transportation costs. Brazilian logistics costs² are around 12.3% to 26% of the value of the national Gross Domestic Product (GDP), reaching 26% of gross revenue for mining, 22% for paper and cellulose, and 21% for agribusiness; while in the United States, logistics costs are around 8.5% of GDP, and only 5.5% for the agricultural sector (CNT, 2018; Deloitte Access Economics, 2019; FDC, 2017; Gouvea and Montoya, 2014; ILOS, 2020; Ministério dos Transportes, 2012, 2007; Plaza et al., 2020; Rodrigue, 2020; United States International Trade Commission, 2012). The interregional competitiveness in the Brazilian domestic market is also

¹ Net tonne-kilometer (TKU) is a unit of measure of freight transportation that represents the sum of products' total weight moved by paid transport over the network, multiplied by the transportation distance (ANTT, 2003).

² Logistic costs comprise transportation (58%), inventory carrying (23%), warehousing (11%), and administrative costs (8%) (Rodrigue, 2020).

hampered by high logistical costs, affecting the economic growth of less developed regions or of regions located on new agricultural frontiers (such as the North and the Northeast regions), due to inadequate and inefficient transportation options (Ministério dos Transportes, 2012).

Table 1 shows the modal split of freight transportation and the logistic costs of several countries. Brazil's road share is comparable to those of smaller countries, while countries that also have large territorial dimensions have higher shares of railways, waterways, and pipelines, which are more suitable for medium and long distances. This unbalance reflects on Brazil having higher logistic costs, comparing with other countries with similar levels of economic development and composition of national economy (Ministério dos Transportes, 2012; Rodrigue, 2020).

Table 1. Modal split of freight transportation (as of 2019, in %TKU or %TKM³) and logistic costs (in %GDP) in different countries.

Country	Modal split of freight transportation (% of TKU or TKM)					Logistic costs (% of GDP)
	Road	Railway	Cabotage	Pipeline	Inland waterway	
Russia	6%	60%	1%	31%	2%	19%
Canada	19%	34%	3%	40%	4%	9%
Australia	27%	55%	14%	4%	0%	10%
China	35%	14%	25%	3%	23%	18%
United States	43%	27%	3%	22%	5%	9%
European Union	50%	11%	32%	3%	4%	-
Japan	51%	5%	44%	0%	0%	9%
Austria	60%	28%	-	2%	11%	-
Brazil	61%	21%	12%	4%	2%	12.3% - 26%
Germany	71%	18%	-	3%	8%	9%
France	85%	9%	-	4%	2%	12%

Sources: CNT (2018); European Commission (2021a); ILOS (2020); Rodrigue (2020); Stapran (2018).

Considering particular conditions and for certain cargo flows, waterway freight can be 62% more economical than road freight, while railway freight can be 37% less expensive than road freight. Thus, a balanced transportation matrix should lead to a reduction in transportation costs, significantly reducing logistic costs (Ministério dos Transportes, 2012). In Brazil, commonly a train composition has over 80 wagons and transports over 7,000 tonnes (Péra and Caixeta-Filho, 2021), while the 7-axle dry bulk trailer - used to transport grains - has a capacity of 37 tonnes (Péra, 2022).

³ "A tonne-kilometre, abbreviated as tkm, is a unit of measure of freight transportation which represents the transportation of one tonne of goods (including packaging and tare weights of intermodal transportation units) by a given transportation mode (road, rail, air, sea, inland waterways, pipeline etc.) over a distance of one kilometre" (Statistics Explained, 2021c).

In addition, railways and waterways are more efficient energetically and environmentally and emit less greenhouse gases (GHG) than the road mode. Therefore, a shift towards a balanced transportation matrix is aligned with a greener logistics and the growing awareness of the environmental problems and negative externalities caused by the transportation sector. Green logistics is a broad concept and energy efficiency and emissions control are just some of its dimensions (Péra, 2022; Rodrigue, 2020).

In the past few years, Brazilian government has focused on achieving a more balanced and rational transportation matrix through initiatives such as the PNL(T) - National Logistics (and Transportation) Plan (EPL, 2018, 2021a; Ministério dos Transportes, 2007, 2012), the Growth and Acceleration Program (PAC), and privatization efforts (United States International Trade Commission, 2012). The PNL(T) aims to gradually give greater balance to the transportation matrix through the proper use of each mode according to its main vocation. Therefore, in the long term there will be a reduction in the road mode participation as it will be focused on meeting demands that need greater capillarity, short-haul movements between farms and rail or barge terminals, and urban and metropolitan distribution; and there will be an increase in the relative participation of large capacity modes (EPL, 2021a; Ministério dos Transportes, 2012, 2007). The PNL(T) methodology has evolved through time and in its latest version, it encompasses a strategic analysis layer that plans logistics and transportation systems from a territorial, integrated, and dynamic vision, based on intermodality and network efficiency, using new databases and new simulation and evaluation models (EPL, 2021a).

The PNL(T)'s idea is to evaluate transportation infrastructure projects in different scenarios and time horizons (15 and 30 years), where the impacts and possible risks and returns to society associated with these projects are estimated before the execution of any action plan. These scenarios' analysis will guide the development of the Sectoral Plans (terrestrial, ports, waterways, and national airways), bringing elements that will allow the prioritization of projects and a more assertive planning of actions (EPL, 2021a). However, the PNL(T) only considers existing projects and does not propose the development of new and more suitable projects.

Tables 2 and 3 show the results of the PNL-2035, in both TKU and VKU⁴.

⁴ Net value-kilometer (VKU) is a unit of measure of freight transportation that represents the sum of products' total monetary value moved by paid transport over the network multiplied by the transportation distance (ANTT, 2003; EPL, 2021a). The difference between TKU and VKU is that TKU measures weight (tonnes) while VKU measures monetary value.

Table 2. PNL-2035's results – transportation matrix (in %TKU).

Modal	Scenarios										
	2017	1 - Projects in progress	2 - Planned projects + Referential	3 - Planned projects + Transformative	4 - Planned projects and "BR do Mar" + Referential	5 - Planned projects and technological innovations + Referential	6 - Projects proposed by society + Referential	7 - Planned projects and authorized railways + Referential	8 - Merge of scenarios 1 to 7 + Transformative	9 - Main opportunities + Referential	2020 transport network
Road	66.2%	54.5%	51.4%	52.5%	50.8%	46.9%	39.5%	51.6%	32.2%	41.4%	65.0%
Railway	17.7%	30.7%	34.6%	33.9%	31.1%	36.4%	42.7%	34.2%	47.2%	42.9%	21.1%
Cabotage	9.2%	8.8%	8.5%	8.1%	10.6%	10.1%	8.3%	8.6%	12.0%	9.6%	8.4%
Waterway	5.6%	4.5%	4.2%	4.1%	6.0%	5.2%	8.1%	4.2%	7.2%	4.5%	4.0%
Airway	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Pipeline	1.3%	1.4%	1.3%	1.3%	1.4%	1.4%	1.3%	1.3%	1.3%	1.6%	1.4%

Source: EPL (2021a).

Table 3. PNL-2035's results – transportation matrix (in %VKU).

Modal	Scenarios										
	2017	1 - Projects in progress	2 - Planned projects + Referential	3 - Planned projects + Transformative	4 - Planned projects and "BR do Mar" + Referential	5 - Planned projects and technological innovations + Referential	6 - Projects proposed by society + Referential	7 - Planned projects and authorized railways + Referential	8 - Merge of scenarios 1 to 7 + Transformative	9 - Main opportunities + Referential	2020 transport network
Road	83.3%	68.5%	67.2%	68.9%	65.4%	60.2%	47.2%	66.1%	41.5%	52.6%	83.7%
Railway	4.2%	19.0%	20.4%	19.3%	20.4%	26.6%	38.6%	21.5%	43.7%	34.9%	4.9%
Cabotage	5.8%	6.4%	6.3%	6.1%	7.7%	7.0%	6.0%	6.2%	6.9%	6.7%	6.1%
Waterway	5.5%	4.6%	4.7%	4.4%	5.1%	4.8%	6.8%	4.7%	6.7%	4.3%	3.7%
Airway	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.7%	0.7%
Pipeline	0.7%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.7%	0.9%	0.9%

Source: EPL (2021a).

The PNL-2035 preliminary version concluded that, considering statistical modeling errors, an adequate rational transportation matrix would be achieved when the sum of the mode shares for railways, waterways, and cabotage represents more than 43.8% (in %TKU), which occurred in all scenarios but the one that considered the same transportation infrastructure network of 2020. The 10 PNL-2035 scenarios differ in the selection of infrastructure projects, by using economic referential parameters or their reconfiguration to a transformative context, and whether regulatory changes and technological innovations are incorporated (EPL, 2021b, 2021a).

It should be noted that road and airway modes are largely responsible for the transportation of high value-added goods in the Brazilian territory, even in the simulated scenarios. Railroads with capacity to transport containers could provide an alternative to these modes (EPL, 2021a).

Considering logistical costs and GHG emissions, a matrix with greater participation of other modes than road transportation would be desirable. However, it is important to highlight that the availability of infrastructure is the first but not the only factor that motivates modal shift. Economic, market, and performance indicators (e.g., speed, reliability, frequency, and safety) are other determinants that strongly influence modal choice (Ministério dos Transportes, 2012; Rodrigue, 2020). Multimodal transportation faces additional operational challenges, such as: effort necessary to coordinate activities performed by different agents; possible longer delivery times, especially for door-to-door transportation; additional costs related to transshipment, and increase in post-harvest losses (Péra, 2022; Plaza et al., 2020). Several countries and regions, like European Union and China, aim towards a more balanced transportation matrix, but are facing mixed results despite several measures. Thus, it is also important to know and understand what has been occurring in other countries to assist Brazil in this change.

Furthermore, there is a significant difference between the modal split of freight transportation to export markets and to domestic market. Generally, Brazil's freight transportation to the domestic market is done almost exclusively by road (for instance, 98%⁵ for maize and 97% for soybean as of 2019 in tonnes), while the transportation matrix for export markets is balanced (31% by road, 50% by rail, and 20% by barge for maize and 49% by road, 38% by rail, and 13% by barge for soybean as of 2019 in tonnes) (Péra et al., 2021).

Nonetheless, the modal share of railways and waterways in shipments to export markets could be even higher if there was additional capacity. Maize and soybean's volume transported in railways and waterways increased significantly from 2010 to 2019 (27.6 million tonnes and 15.1

⁵ This modal split of freight transportation does not consider short-haul trucks (pre-haul) in order to avoid double accounting (Péra et al., 2021).

million tonnes, respectively), but the infrastructure did not have enough capacity to transport the increasing exported volume; so, the increase of volume in the road mode was much higher (34.3 million tonnes) (Péra et al., 2021). Thus, there are several planned projects focused on linking the areas with high production of commodities to the exporting ports. Among them, the main railways and railways' stretches planned or undergoing construction are Ferrogrão, North-South Railway (FNS), West-East Integration Railway (FIOL), Rumo Malha Norte, New Northeastern Railway (NTN), Authorized Transportation Railway Olacyr de Moraes (FATO), Center-West Integration Railway (FICO), and West Export Corridor (Nova Ferroeste) (Governo do Estado do Paraná, 2022; Péra, 2022; Rocha, 2020). Figure 1 shows these railways, including the existing stretches.

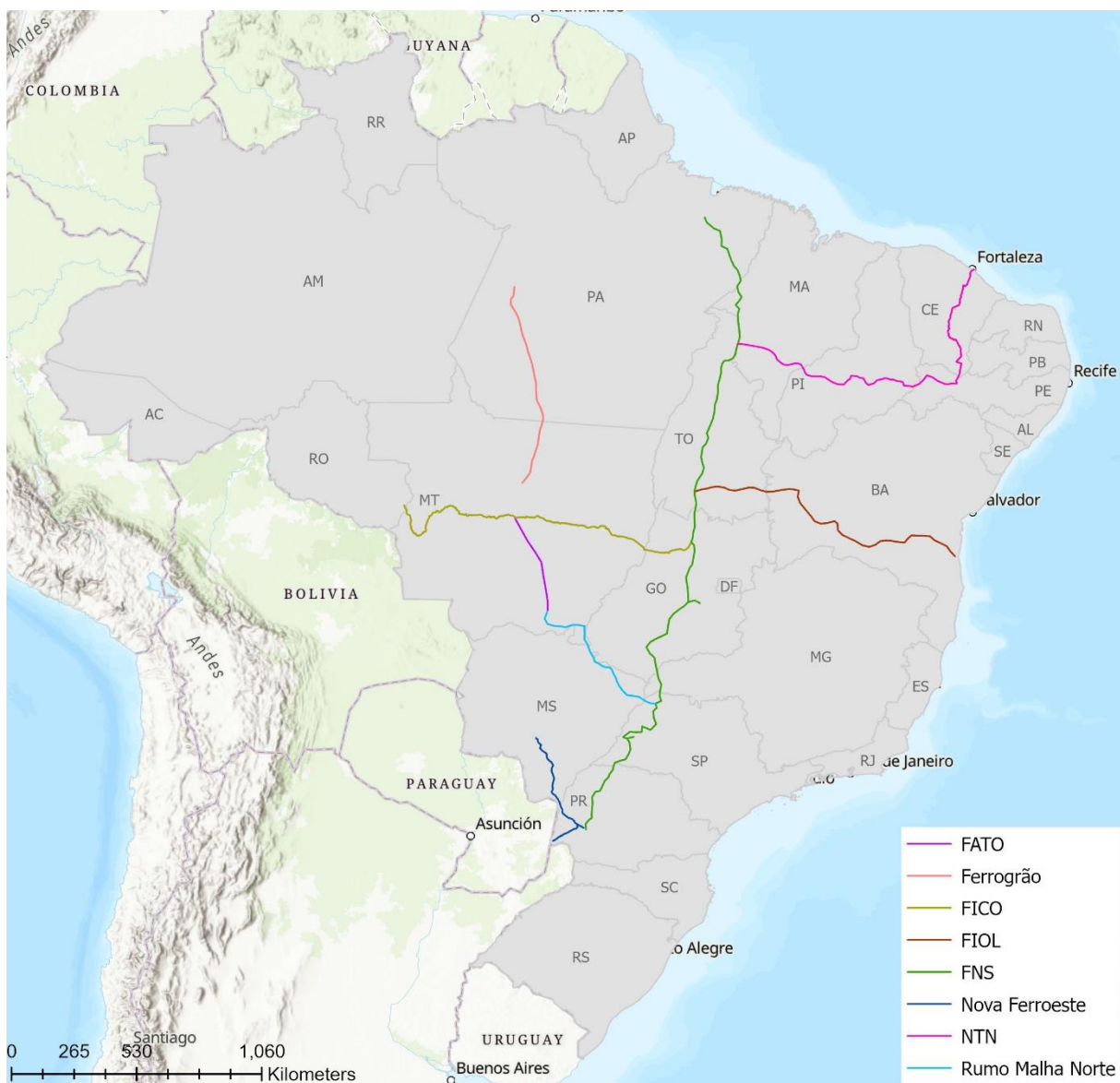


Figure 1. Brazil's main railways and railways stretches planned or under construction.

Source: EPL (2021c).

Although freight transportation to export markets is extremely important to Brazil economic performance, the flows to domestic market should not be overlooked. Firstly, the freight transportation volume to Brazilian domestic market is much higher (67% as of 2017) than to the export (22%) and import markets (11%) (EPL, 2021d). Secondly, several products, especially raw materials, travel long distances to reach their consumers using road transportation and would benefit from more efficient modes such as railways and waterways. Unfortunately, there are only some projects focused on the domestic market and most of them are part of projects whose main goal is to improve export flows, while even fewer projects that are dedicated exclusively to domestic market are on the federal government's priorities list.

This is an adverse scenario for Brazilian industries that depend on raw materials produced in other regions of the country, such as the poultry and pork sectors of Santa Catarina (SC) and Rio Grande do Sul (RS), located in the South region of Brazil. The main inputs for poultry and pig feed are maize and soybean meal. The states with the highest surplus of maize are Mato Grosso do Sul (MS), Goiás (GO), and Mato Grosso (MT) (Safras&Mercado, 2022a), located in the Center-West region. The long distances from MS, GO, and MT to SC and RS can easily reach more than 1,000 km and are currently traversed by road, as there is no railway linking these states.

On the other hand, the design of new railways has evolved in the past few years, with the use of Geographic Information Systems (GIS) integrated with methods such as the Analytic Hierarchy Process (AHP). GIS are databases that use spatial location to collect, store, manipulate, integrate, analyze, report, and illustrate geographical data in computer memory (EDLP, 2016a; Hasany and Shafahi, 2017; Mohseni et al., 2016; Rodrigue, 2020; Song et al., 2021). GIS have been used in railway, highway, and transportation network design and planning to calculate distance and travel time between two points, to find the best path between origin and destination, to improve horizontal and vertical alignment, to increase accuracy in the calculation of the total cost (especially regarding construction costs), to determine characteristics and feasibility of potential locations for facilities, terminals, and stations, and to generate maps and analysis, among other uses. The AHP is a weighted linear summation method used to solve multi-criteria decision-making (MCDM) problems, usually complex systems such as railway design that have many hard-to-quantify and conflicting factors. The problem is divided into a hierarchical structure of sub-problems that are analyzed individually and then integrated in a logical and consistent way. The weights are calculated by a group of experts that compares the relative importance between each pair of criteria. Thus, AHP combines qualitative experts' experience and quantitative multi-criteria analysis (EDLP, 2016a; Mohseni et al., 2016; Song et al., 2021; Suárez-Vega et al., 2011).

For instance, Song et al. (2021) proposed a two-stage method based on GIS and AHP to design a railway. The first stage assesses environmental impact and in the second stage, an automated railway design is performed. The method is applied to a real-world case in China and compared to the best manually designed alternative produced by experienced human designers. The starting and ending points of the railway were given.

In Brazil, the preliminary engineering studies of the Ferrogrão used GIS combined with AHP to select the best railway corridor and path alternative of the main line between Sinop (MT, located in the D4 grid of Annex A – “Brazil’s main railways, ports, and cities”) and Itaituba, in the state of Pará (PA, located in the D3 grid of Annex A). The starting and ending points of the railway were previously defined by the Brazilian government, just like all the main new railways projects. This preliminary study did not consider an intermediary terminal in the railway, as significant cargo volume outside of the origin and destination regions was not observed in a preliminary demand study (EDLP, 2016a). In the following reports, the intermediary terminal in Matupá (MT, located in the D4 grid of Annex A) was included, after the designers have analyzed the demand capture results (EDLP, 2016b, 2016c). The demand forecast was detailed in a specific report, with the designers selecting the products based on the states’ production and consumption data and defining the area of influence through a demand capture gravitational model (EDLP, 2016c).

There are several studies focused on aspects of transportation planning and design. The main problems considered are the selection of the best path (Cruz-Chávez et al., 2020; Hasany and Shafahi, 2017; Kosijer et al., 2012; Song et al., 2021; Ye et al., 2020), determining the best horizontal and vertical alignment (Ahmed et al., 2020; Jha, 2013; Lai and Schonfeld, 2016; Samanta and Jha, 2011; Song et al., 2021), location of intermodal terminals (Arnold et al., 2004; Isler et al., 2021; Plaza et al., 2020), urban transit stations (Ahmed et al., 2020; Horner and Grubestic, 2001; Lai and Schonfeld, 2016; Samanta and Jha, 2011) or facilities (Mohseni et al., 2016; Rahemi et al., 2020; Suárez-Vega et al., 2011), and evaluation and selection of infrastructure projects (Alireza Seyedvakili et al., 2020; Apivatanagul and Regan, 2010; Branco et al., 2020; De La Cruz et al., 2010; Gallardo et al., 2021; João, 2021; Maia and Couto, 2013; Péra, 2022; Rocha, 2020; Silva-Neto, 2018; Yamada et al., 2009; Yamada and Febri, 2015). Nevertheless, to the best of the author’s knowledge, none of these studies proposed a heuristic procedure to design a new railway that includes the selection of the starting, intermediate, and ending points and the definition of the area of influence and potential cargo.

Another component of the logistics network is the warehouse. This structure stores goods for an extended period, such as weeks and months, with a supply-driven buffer related function, and releases the products upon demand. Warehouses are utilized to manage unexpected demand,

to stock the produced surplus, to deal with seasonality, to consolidate cargo, or to stock after manufacturing. For non-perishable goods that can be stored at a low cost, such as grains, warehousing is a common strategy (Rodríguez, 2020). In Brazil, the static storage capacity is not enough to meet the grains produced volume, which leads to product and economic losses to the related actors (João, 2021).

Therefore, the research question⁶ of this thesis is how to improve the Brazilian logistics network for the domestic market of agricultural products in a more sustainable way. To answer this question, this thesis proposes a two-level optimization model for transportation and warehouse networks integrated with a GIS.

In the first level, a railway network design model defines a new railway that connects the Center-West and South regions and maximizes the benefit-cost ratio. In the second level, a linear programming model optimizes the Brazilian agricultural products' logistic network, finding the Origin-Destination (O-D) flows and storage volumes that minimize the total logistic cost and the carbon dioxide (CO₂) emissions. Hence, the proposed model designs a new railway to link the Center-West and the South regions; selects the location of warehouses that need to increase the static capacity and determines the necessary volume; assesses the most used transportation infrastructures; and finds the most promising entry points to import maize from Paraguay, Argentina, and other countries.

The research objectives are:

- i. Develop a railway network design model to propose a new railway that includes the criteria to define the starting and ending points of the railway and its intermediate terminals and to determine the area of influence and the potential cargo.
- ii. Apply the proposed railway network design model to create a new railway that links the Center-West and South regions of Brazil.
- iii. Develop a GIS-based optimization model for transportation and warehouse networks, to improve the supply of Brazilian domestic market of agricultural products in a more sustainable way.
- iv. Evaluate the new railway performance against the future Brazilian multimodal network, assessing the methodology performance and the solution quality.
- v. Identify the main logistic infrastructures used in the domestic transportation.
- vi. Compare the modal share of the improved Brazilian transportation network with other countries of comparable size.

⁶ This thesis' research question, second level model (optimization model for transportation and warehouse networks), and case study are inspired by the "Samoa" Project, developed by the Group of Research and Extension in Agroindustrial Logistics (ESALQ-LOG, 2020), with the participation of the author of this thesis.

- vii. Understand the experience of other countries of similar size in reaching a more balanced transportation matrix.

The research hypotheses are:

- i. The proposed railway network design model can create new railways with high potential cargo.
- ii. A new railway linking the Brazilian Center-West and South regions can improve the domestic supply of maize, soybean, and soybean meal in a more sustainable way.
- iii. Increase in the static storage capacity of bulk warehouses can improve the domestic supply of maize, soybean, and soybean meal in a more sustainable way.
- iv. The proposed two-level optimization model for transportation and warehouse networks integrated with a GIS can improve the maize, soybean, and soybean meal supply.
- v. The proposed method can generate a more balanced and rational transportation matrix.

The remaining parts of this thesis are organized as follows. Chapters 2 and 3 present the literature review. Firstly, chapter 2 explores the different characteristics of each transportation mode and shows Brazil's and some relevant countries' historical background and current logistics infrastructure. Then, chapter 3 presents studies on freight transportation planning and design and papers that use GIS, worldwide and especially in Brazil.

Chapter 4 details the case study used in this thesis to illustrate the proposed model and defines the two-level optimization model for transportation and warehouse networks integrated with GIS. It includes the mathematical models, the solution method, and the used parameters and multimodal transportation network.

Chapter 5 presents the computational experiments, their results and discussion. Finally, chapter 6 shows the concluding remarks of this thesis.

2. TRANSPORTATION MODES AND LOGISTIC INFRASTRUCTURE

To achieve a more balanced and rational transportation matrix, it is important to understand the differences among the transportation modes and the determinants of modal choice, and to learn from other countries' experience. Thus, this first chapter of literature review presents an analysis of the transportation modes and of the logistic infrastructure in different countries.

In section 2.1, there is an overview about the different transportation modes and their main characteristics. It also presents the main factors that influence modal choice.

Section 2.2 shows the logistic infrastructure of Brazil and some relevant countries, as the transportation infrastructures' availability is a major determinant in the modal choice. Section 2.2.1 portrays Brazil's historical background and current logistics infrastructure. Section 2.2.2 presents the European Union path towards a more balanced and sustainable modal split of freight transportation.

The following sections show some relevant countries' historical background and current logistics infrastructure: the United States (section 2.2.3), China (section 2.2.4), Canada (section 2.2.5), Russian Federation (section 2.2.6), and Australia (section 2.2.7). Lastly, section 2.2.8 presents a comparison among these countries.

These five other countries were selected as they also have continental dimensions, just like Brazil, and transport millions of tonnes of products from producing centers to exporting ports or consumption centers across long distances. In addition, these countries aim to achieve a more balanced and rational transportation matrix. On the other hand, their modal split of freight transportation is more balanced (as seen in Table 1), and their overall transportation infrastructure is better (as shown in section 2.2.8) than Brazil's. Thus, they serve as positive and negative examples on how to attain an improved logistics network with focus on sustainability.

2.1. Transportation modes

Each transportation mode has important operational and commercial advantages and characteristics. The modal choice depends on availability, distance, quantity, value of the goods, cost, trip time, and quality tradeoffs. A key factor in the cost structure is the terminal's loading and unloading costs and delays, which are independent of the distance traveled. Road has a lower cost function for smaller distances, but it increases faster than railways and waterways' cost function. For long distances - generally - pipelines are a superior competitor for the liquid traffic; waterways

are dominant for the low cost, bulk cargo; and airways are suited for high value, small sized cargo (Thompson and Sondhi, 2002).

A freight transportation chain can consist of three phases: pre-haul (or first mile), long-haul (or door-to-door), and end-haul (or last mile). Usually the pre-haul and the end-haul are carried out by road, while the long-haul is executed by road, rail, water, air, or a combination of these modes. A multimodal freight transportation occurs when goods are moved in a sequence of at least two different modes. Its main disadvantage when comparing to unimodal road transportation is the need to haul the goods from trucks to trains, ships, or barges in a transshipment multimodal terminal. This operation is time consuming and costly, negatively impacting on the transit and delivery times (when terminal operations are inefficient) and on post-harvest losses (Archetti et al., 2022; Péra, 2022; Steadieseifi et al., 2014). A particular type of multimodal transportation is the intermodal freight transportation, in which the load unit (e.g., a Twenty-foot Equivalent Unit - TEU - container) is not changed during the transportation chain and the goods are not handled when changing modes (Archetti et al., 2022; Steadieseifi et al., 2014).

Generally, it is more advantageous to use road mode up to 500-750 km, railways between 500-750 and 1,500 km, and waterways over 1,500 km of distance (Rodrigue, 2020; Thompson and Sondhi, 2002). However, for most origins and destinations, railways or waterways are not available, thus a higher cost mode will be used. In addition, rail and waterways must be accessed through terminals, thus frequently requiring a pre-haul trip done by road that changes the cost structure (Rodrigue, 2020). Although road transportation can be more expensive, its advantages include convenience, flexibility, accessibility, adaptability, and especially perceived quality of service, so it can still be dominant even with higher costs (Chaudhury, 2005).

The modal choice can be disturbed by external costs, which happens when the provider or user does not perceive or pay for the costs of the transportation infrastructure or capacity consumed. It includes air and noise pollution, safety, congestion, climate impact, and habitat damage. For example, heavy trucks do not pay their full share of the costs to build and maintain highways in some countries, which favors road mode (European Commission, 2021b; Thompson and Sondhi, 2002). Studies showed that railways' external costs are lower than road's and that the internalization of the external costs could correct the modal split of freight transportation and increase the efficiency of the transportation system (Chaudhury, 2005; European Commission, 2021b).

As previously mentioned, the transportation infrastructures and networks' availability are major determinants in the modal choice. The absence of important modes limits shippers'⁷ choice and accessibility to markets and generates an inefficient commercial environment. Thus, transportation provision is considered a major factor in economic development, and areas with limited modal availability tend to be less developed (Rodrigue et al., 2013). Usually, railway construction is much more expensive than road construction due to the much smaller maximum allowable slope, to the much greater minimum value of the curve radius, and to the more costly superstructure equipment of railway tracks (Alireza Seyedvakili et al., 2020). Consequently, rail mode has responded slowly to changes in transportation demand in terms of cargo characteristics and customer necessities; for instance, failing to co-operate with transportation chain partners in offering door-to-door service (Islam and Blinge, 2017).

Islam et al. (2016) showed that shippers require freight service that have (in order of importance) service reliability, competitive cost of door-to-door delivery, service availability, safety and security, and environmentally friendly transportation service for the same price. In addition, customer needs include easy access, accurate information provision, and adaptability of service. To offer a competitive cost for a reliable service, it is necessary to reduce costs; for instance, by operating heavier and longer trains, with wider loading gauge, at higher average speed, and having a better use of wagon space and other assets.

2.2. Logistic infrastructure

2.2.1. Brazil

Brazil is the fifth largest country in the world, with 7.7 million km², and has the twelfth highest GDP, with US\$1.4 trillion as of 2020 (World Bank, 2022). Brazil's top exporting products are iron ore, soybean, crude petroleum, raw sugar, maize, soybean meal, sulfate chemical wood pulp, and frozen bovine meat (SECEX, 2022; Simoes and Hidalgo, 2011; USDA, 2022, 2021).

The first transportation plans documented in Brazil are from the first half of the 19th century, when the interiorization of the Brazilian territory was still not expressive and the long-distance routes were carried out basically by maritime navigation. Most transportation plans were developed between 1808 and 1890, considered intermodality, and focused on transporting both people and goods, mainly due to the characteristic of rail mode, that was the main land transportation technology available at the time (EPL, 2021a).

⁷ "The shipper is a transportation customer who needs to move commodities from one point to another. The carrier provides transportation services for these demands" (Apivotanagul and Regan, 2010).

After the Proclamation of the Republic (1889), significant institutional changes occurred in the transportation management system. Highways have become the type of infrastructure that could be built with agility and in line with the development interests of government officials, gaining the focus of federal actions. There were separated plans by transportation mode or focused on specific demands, and the systemic view of the network was lost. It resulted in an unbalanced transportation matrix based on road mode, with high transportation costs due to large traveled distances, few alternative modes, and difficulties in intermodality, e.g., lack of connections and transshipment terminals. In addition, a planning culture that prioritizes the transportation mode over the characteristics and needs of demand was established, resulting in overlapping, conflicting or disconnected public and private investments (EPL, 2021a).

This scenario lasted until 2001, with the institutional restructuring of the transportation sector. Since then, the Ministry of Transportation resumed discussions on the process of planning and formulation of the transportation policy involving an integrated logistics chain, originating the National Logistics and Transportation Plan – PNL(T) (2007).

Ever since 1950s, Brazil's transportation matrix is based on road mode (Ministério dos Transportes, 2012). Historically, there is an underinvestment in railways and waterways, and there is a regional variation in transportation infrastructure within the country. As of 2021, Brazil's road network covered more than 1.7 million km, with 215,000 km of paved roads; railways had more than 30,000 km; and waterways around 20,000 km, with potential to develop another 22,000 km (CNT, 2022; Péra and Caixeta-Filho, 2021; United States International Trade Commission, 2012).

Regarding road mode, trucking services and fleets are unevenly distributed throughout the country, creating transportation bottlenecks during peak times such as the harvest period. Another difficulty during peak times is the road congestion, which also raises transportation costs. Poor road conditions can lead to grains or oilseeds' losses, frequent delays, high repair and maintenance costs for trucks, and road accidents, increasing the operating costs in 28% comparing with trucks operating on paved roads in optimal condition (United States International Trade Commission, 2012). In a 2021 survey of paved roads, only 38% of the surveyed roads were in good or great condition (CNT, 2022). Although the long-term goal is to obtain a more balanced transportation matrix, initiatives such as PNL(T) and PAC also focus investments in improving and expanding road networks in Brazil, as they are faster to implement than railroads and can bring short terms results.

Waterways transport around 15% of Brazil's cargo. The regions with the greatest hydrographic potential are still not fully explored, even though their levels of economic activity are sufficient to generate demand for transportation (Gouvea and Montoya, 2014; Ministério dos

Transportes, 2012). Investments are needed in facilities, in improvements to navigable rivers, and in the construction of locks near hydroelectric plants to allow the traffic of barges (United States International Trade Commission, 2012). When compared to road and rail modes, waterways have presented the best costs of air and noise pollution, accidents and external events (measured by thousand TKM) (Garcia et al., 2019)

The PNLT-2012 set the goal of waterborne transportation reaching 25% of the transportation matrix by 2025. This could be achieved by using an expanded concept of Short-Sea Shipping (SSS), as part of freight intermodal transportation chains and not only considering small cabotage (when the origin and the destination are within the country territory) (de Valois et al., 2011).

There were eight inland waterways transporting agricultural and mineral products, construction material, and fertilizers, but only the Tietê-Paraná waterway connects population or economic centers; so, most waterways require transshipment operations to transport products to their final destination (United States International Trade Commission, 2012). New inland waterways were created in the Northern region of the country due to substantial investments from the private sector after the establishment of the Ports Regulatory Framework. It included the construction of private terminals outside the traditional public ports area (Péra et al., 2021).

For every operational kilometer of railway, there are 21.5 km of roads and 2.24 km of waterways, as only one third of Brazil's railway network is operational. About 50% of Brazil's railway network is in the South and Southeastern region (states of São Paulo, Minas Gerais, Rio de Janeiro, and Rio Grande do Sul). Except for Rio de Janeiro, the three other states are some of the higher producers of agricultural commodities (more than 5.6 million tonnes) and their railway density is above 5.575 km/1,000 km². On the other hand, Mato Grosso, in the Center-West region, is the highest producing state and has a railway density of only 0.120 km/1,000 km² (Péra and Caixeta-Filho, 2021; United States International Trade Commission, 2012).

In the mid-1990s, the railway network was privatized, after years of underinvestment and limited maintenance. Around 95% of the rail network is operated by five private groups and two state-owned companies, under 12 different concessions. The concentration of rail operators and the limited competition have led to monopoly pricing, and the networks under concession are relatively disconnected. Currently, two-thirds of the rail network is not operational, due to the low demand in some regions and to the high investment needed for restructuring (Péra and Caixeta-Filho, 2021; United States International Trade Commission, 2012).

The predominant railway concession model in Brazil is the vertical, in which the concessionaire is responsible for the freight transportation service and operations, and the

investment and expansion of the rail infrastructure. The average speed has been constantly around 13-22 km/h, while in the United States is circa 80 km/h. On the other hand, fuel consumption in railways transporting agricultural products has been decreasing, reducing the emission of pollutants. Another positive change is the increase in productivity, through the reduction of the number of formed trains, the increase in the transported volume over time, and the higher efficiency in the use of wagons (CNT, 2022; Péra and Caixeta-Filho, 2021).

In the last few years, there were significant changes in the railway sector, with the improvement of the regulatory environment, new concessions, and, especially, the possibility of building railways by the private sector upon authorization with the Railway Authorization Program, set in 2021. It is expected that this program is going to generate an increase in the number and in the modernization of railways, in both short and long-lines, as well as an increase in the competition in the railway sector, enabling small, medium, and large shippers to use the network (Péra and Caixeta-Filho, 2021).

Regarding the transportation of agricultural products, in the last few years there has been a significant increase in the market share of Rumo Malha Norte and of the North stretch of the FNS, both part of the Arco Norte network, while there was a decrease in the market share of Rumo Malha Sul (Péra and Caixeta-Filho, 2021). This is a sign that there is demand for railways connecting other regions apart from the South and Southeastern regions.

From 2010-2020, there was an increase in the volume of soybean and maize transported by railways of more than 100%, and of around 80% for sugar. Soybean meal volume was practically the same, and there was a reduction in the transported volume of limestone, wheat, and ethanol (Péra and Caixeta-Filho, 2021). In 2020, the average distance between origin and destination was of 585 km for sugar (varying from 271 to 1,195 km), 917 km for ethanol (from 307 to 1,453 km), 896 km for fertilizers (117 to 2,195 km), 974 km for maize (482 to 1,648 km), and 883 km for soybean (230 to 2,100 km) (Péra and Caixeta-Filho, 2021). Regarding seasonality, soybean is transported mainly in the first semester, maize (due to the winter or second-crop) and sugar transportation are concentrated in the second semester, and soybean meal and fertilizers' shipments are relatively stable throughout the year (Péra and Caixeta-Filho, 2021).

There was an intense growth in the production of agricultural commodities in Brazil between 2010-2020, especially of grains. Their transportation by railways has timidly followed the production growth, mainly because the railways' capacity was lower than the demand for transportation, especially towards exporting ports (Péra and Caixeta-Filho, 2021).

Péra and Caixeta-Filho (2021) analyzed the railway network and found three non-connected clusters in the transportation of agricultural products. Cluster I comprises the states of

Minas Gerais (MG), Goiás (GO), São Paulo (SP), and Mato Grosso (MT). The main origin is the terminal of Uberaba (MG), and the main destinations are the exporting ports of Santos (SP) and Vitória (state of Espírito Santo - ES). The FNS, especially its North stretch, composes the cluster II, from Porto Nacional (state of Tocantins - TO), Porto Franco (state of Maranhão - MA) and Palmeirante (TO) to the exporting port of São Luís (MA). Lastly, cluster III includes the states in the Southern region of the country and a small region in the South of São Paulo, that haul goods to the exporting ports of Paranaguá (state of Paraná - PR) and Rio Grande (state of Rio Grande do Sul - RS). It is expected that the new railway projects connect these clusters, forming a highly connected network with transportation in both directions (Péra and Caixeta-Filho, 2021).

Figure 2 shows the Tietê-Paraná waterway and the railways, railway terminals, and exporting ports of the three railway clusters of the transportation of agricultural products. The railways include inactive, under construction, and planned stretches and show the expected connected network.



Figure 2. Tietê-Paraná waterway and the three clusters of the transportation of agricultural products.

Sources: prepared by the author, based on data from EPL (2021c) and Péra and Caixeta-Filho (2021).

Other investments in infrastructure from the private sector comprise the expansion and integration of the rail network through concessions to private companies, and investments in local road networks, storage and warehouse facilities, and port terminals by many agricultural producers (United States International Trade Commission, 2012).

2.2.2. European Union

In 2011, the European Union (EU) published the “White Paper on transport – Roadmap to a single European transport area” (European Commission, 2011), aiming to “define a vision for a competitive and sustainable European transportation system, and thus set a framework for the

necessary short to medium-term actions to guide the development of EU transportation policy to meet long-term objectives” (European Commission, 2021b, p. 3). The White Paper’s specific objectives are “to reduce GHG emissions from transport by 60% relative to 1990 levels by 2050; to drastically reduce oil dependency; and to limit the growth of congestion” (European Commission, 2021b, p. 7).

This vision was translated into ten headline goals. One of them was that transportation users should fully pay for the external costs, while benefiting from less congestion, more information and safety, and better service. Another goal considered that freight transportation over short and medium distances (below 300 km) will still be dominated by road mode, so it is important to improve truck efficiency and the use of cleaner fuels, to use intelligent transportation systems, and to enhance market mechanisms, besides encouraging alternative transportation modes (European Commission, 2011).

In addition, for longer distances (over 300 km), EU needs to stimulate efficient multi-modality, through the development of reliable, green, optimized freight corridors in terms of energy use and emissions, with limited congestion and low operating and administrative costs. This way, the objective is to shift 30% of road transportation to railways, waterways, and other modes by 2030, and more than 50% by 2050 (European Commission, 2011).

On the encouraging side, between 2011 and 2018 there were positive developments in the EU. There was the implementation of the 4th Railway Package, which consists in the adoption of six legislative texts ensuring a single market for rail services; the operationalization of nine Rail Freight Corridors by 2015 and another two by 2020; and the connection of 89% of maritime ports to rails by 2017. On the other hand, there has been very limited progress on the “user pays” and “polluter pays” principles, and the prioritization of rail for passengers had a negative impact on rail freight and freight modal shift objectives (AWB RFC, 2021; European Commission, 2021b). Moreover, the ongoing road freight market deregulation will increase the number of East European operators, increasing the competition with local operators and reducing road haulage costs, thus thwarting a modal shift from road to rail (Sternberg et al., 2020).

Figure 3 shows the European Rail Freight Corridors.



Figure 3. European Rail Freight Corridors.

Source: European Commission (2023a).

Unfortunately, despite these measures to increase attractiveness and competitiveness of rail freight, between 2011 and 2018 there was a minimal change in the modal split of containers transportation. Road mode accounted for 75.3% of total inland freight transportation in 2018 (based on TKM performed), rail share was below 20%, and inland waterways' share decreased to 6.0% (European Commission, 2021b; Islam and Blinge, 2017).

Based on 2011 freight transportation performance in TKM, it is possible to make a simple estimation of the inland modal split in case the modal shift goals are achieved (please refer to Table 4), considering that the road mode volume is shifted proportionally to railways and waterways. The achievement of these goals would bring a balanced transportation matrix, helping the European Union reach its objective of a competitive and sustainable transportation system.

Table 4. European Union inland modal split estimation (in %TKM).

Transportation mode	2011 modal split	30% of road transportation over 300 km shifted to railway and waterway	50% of road transportation over 300 km shifted to railway and waterway
Road	74%	61%	52%
Railway	19%	29%	36%
Inland waterway	7%	10%	13%

Source: Statistics Explained (2021b, 2021a).

2.2.3. United States

The United States of America (USA) is the third largest country in the world, with 9.8 million km², and has the highest GDP, with US\$21.0 trillion as of 2020 (World Bank, 2022). The United States competes with Brazil in the exports of soybean, soybean meal, maize, crude petroleum, sulfate chemical wood pulp, and frozen bovine meat, and is a minor competitor in the exports of raw sugar. These are Brazil's top exporting products (Simoes and Hidalgo, 2011; USDA, 2022, 2021).

When the United States became an independent country in 1776, its Constitution provided the Congress with the power to implement transportation infrastructure and regulate commerce among the states. Since then, the federal government has worked on achieving a cohesive and unified transportation network, connecting relatively independent states. The Erie Canal, the Transcontinental Railroad, and the Interstate Highway System are some of these important connecting infrastructures (Committee on Transport & Infrastructure, 2021).

The earliest statewide transportation plan was submitted to the Pennsylvania Legislature in 1791 (U.S. Department of Transportation, 1977). After 1800, main roads and canals were financed by tolls and local improvements were made by the old statute labor system. The first main roads connected the cities with the heaviest traffic that were located along the Atlantic coast (currently U.S. Route 1). Then, the coastal states from New York to North Carolina identified the need to build roads from the seacoast to the Western lands, resulting in four main transmountain roads. By 1850, there were thousands of kilometers of roads and canals spread into all the states, contributing to their internal development as they opened new lands to settlements, reduced the haulage costs from farms to markets, and stimulated industries' development. Due to lower speed and longer distances, canals concentrated heavy freight while roads dominated short-haul and fast-freight business (U.S. Department of Transportation, 1977).

The first railways were built around 1830 and a few had more than 160 km in length. Throughout the time, these short lines were merged into more efficient systems and the gauges

were standardized, allowing long shipments to be carried without the change of railroads or cars. They were built parallel to or close to turnpikes and canals due to topographic reasons, but their operation had higher speed with the steam propulsion (about 32 kilometers per hour) and could haul large tonnages at low cost, having a competitive edge over other modes (U.S. Department of Transportation, 1977).

When the World War I started in 1917, the dominant railway system was suffering with inefficiency and lack of resources for equipment and improvement of terminals. The increase in transported volume due to war efforts led to intense traffic congestion in and around terminals, and the railways were refusing short-haul shipments. Thus, truck transportation increased significantly for short-haul trips, providing shorter delivery times than railroads for almost the same cost. In a few months, railways permanently lost freight transportation of millions of tonnes to roads (U.S. Department of Transportation, 1977).

As road mode grew in importance, the Bureau of Public Roads (BPO) started to conduct highway transportation and planning surveys around 1920 to provide inputs for future programs. In 1937, the BPO used this data to assess the viability of three highways from East to West and three highways from North to South that would meet the need for more and better highways suited for long distance travels. These reports, considering economic and social requirements as the systems' purpose and the need for coordination with other transportation modes, resulted in the National System of Interstate and Defense Highways, that links more than 90% of all cities with more than 50,000 residents (U.S. Department of Transportation, 1977).

The United States current transportation network includes: more than 6.4 million km of public roads; 5,100 civil airports of public use; over 222,000 km of freight rail; 181 ports that handle over 250,000 short tons annually; approximately 2,700 km of levees, 650 dams and 383 major lakes and reservoirs; 19,000 km of commercial inland channels; waterways leading to 926 coastal, Great Lakes, and inland harbors; 241 individual lock chambers at 195 sites nationwide; and over 2.6 million kilometers of pipelines (Committee on Transport & Infrastructure, 2021; U.S. Department of Transportation, 2020).

Regarding pavement conditions of roads and highways, 20% of urban roads and only 5% of rural roads are in poor condition. Truck traffic congestion is concentrated around major metropolitan areas and along major interstate highways. There have been efforts and system improvements to help mitigate congestion, although there has been a decline in peak average speeds in the last few years (U.S. Department of Transportation, 2020).

The United States rail networks are highly developed and link producing areas to major trading hubs and waterways, e.g., Missouri and Mississippi Rivers (United States International

Trade Commission, 2012). Railroads and inland waterways usually transport large volumes of low-value, bulk commodities over long distances (U.S. Department of Transportation, 2020). There are more than 500 railway freight companies in the US, leading to a fierce competitive market with flexible adaptability and low freight rates (Chen et al., 2020). The United States' main waterway is the Mississippi River, which passes through extensive regions of agro-industrial production, reaches ports located at strategic points for both the domestic and export markets, and moves grains and energy products by vessel and barge through its Lower portion. As expected, air carriers generally move high-value, low weight products. Pipelines transport most of the nation's crude oil, petroleum products, and natural gas (Ministério dos Transportes, 2012; U.S. Department of Transportation, 2020).

In the intermodal transportation, it is possible to perform seamless connections of containers between railways and other transportation modes, saving time and the cost of cargo loading and unloading in intermodal traffic. The railway industrial or feeding lines are directly built into the mines, logistics parks, and the ports, so most transportation volume is performed either by different railway companies or by rail-water operation, without road mode (Chen et al., 2020).

In 2018, road transportation was responsible for carrying 60.8% of the weight of all goods shipped in the United States, followed by pipelines (17.6%), railways (8.5%), multiple modes and mail (7.3%), waterways (5.5%), and air (0.1%). Half of the transported volume traveled less than 160 km, while 7.6% was moved for 1,600 km or more. For distances under 1,600 km, road transportation is the main mode, while rail dominates for distances between 1,600 and 3,200 km. Air and multiple modes shipped 50.0% in value for distances over 3,200 km. There has been a 61.1% growth in intermodal rail freight volume since year 2000, including movement of containers by a combination of rail, road, and water modes. (U.S. Department of Transportation, 2020).

Figure 4 shows the United States 2018 freight flows by transport mode and the main road, railway, and waterway networks.

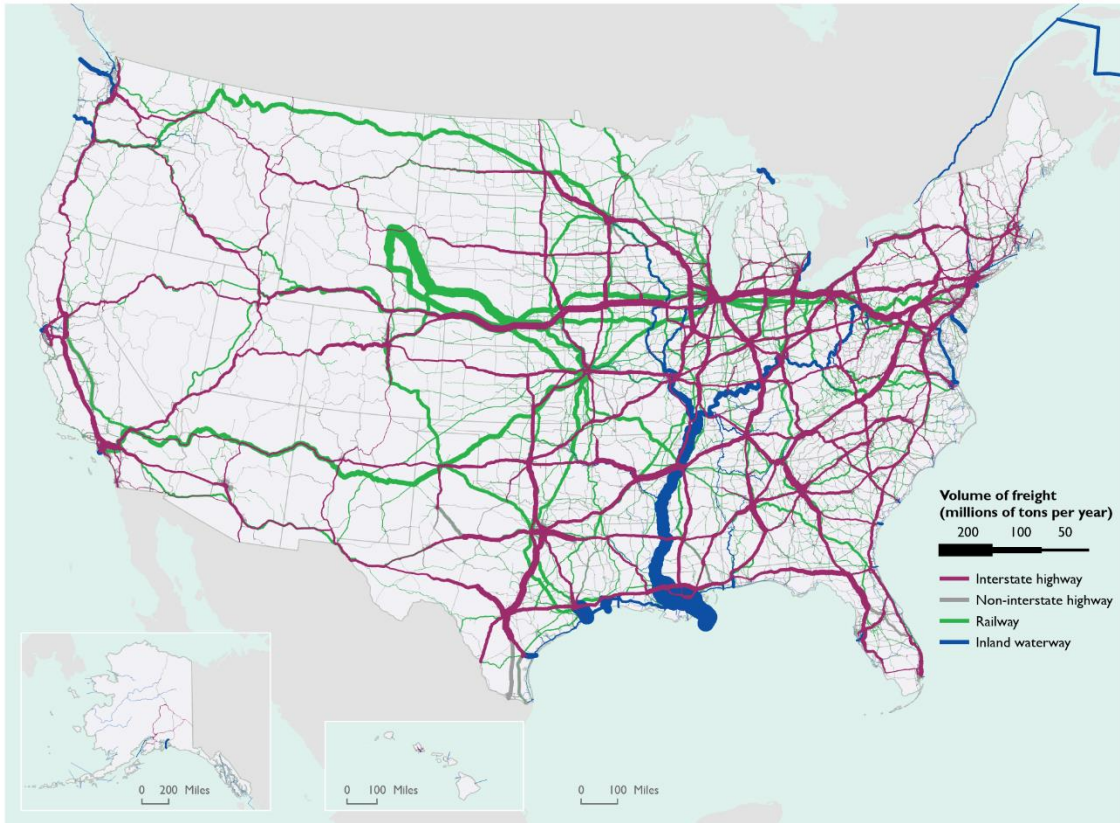


Figure 4. The United States' 2018 freight flows by road, railway, and waterway.

Source: U.S. Department of Transportation (2020).

Natural products and agricultural commodities are produced in widely dispersed but fixed locations and are transported from their rural production areas to metropolitan areas and export markets through an interconnected network of roads, railways, waterways, and pipelines (U.S. Department of Transportation, 2020). Grains (maize, wheat, soybean, sorghum, and barley) are transported by barges, railways, and roads, which display a balance between a high degree of competition in some markets and integration among them. This multimodal network provides a highly efficient and low-cost transportation system that positively influences in the competitiveness of U.S. grains in the world market. From 2003 to 2019, road modal share increased from 49% to 67%, mainly due to a significant increase in the domestic market transported volume (from 187 million tonnes to 365 million tonnes, mostly maize). In the same period, railway modal share decreased from 33% to 22%. Although the transported volume raised to 150 million tonnes around 2006-2010, it returned to 130 million tonnes in 2019, same volume of 2003. Waterways (used by barges) also maintained the same transported volume (around 65 million tonnes), so its modal share reduced from 18% in 2003 to 11% in 2019 (Chang et al., 2021).

In addition, in the last few years there has been an increase in the containerization of agricultural products due to several factors: Asian grain markets are adopting identity preservation

programs to assure shipments contain non-genetically modified organisms; opportunities to export grains through backhaul channels because of the container traffic imbalance in trans-Pacific shipping routes; increase in bulk shipping rates; and shippers' concern in accessing intermodal terminals and achieving reliable delivery times (Lee, 2015).

2.2.4. China

China is the fourth largest country in the world, with 9.6 million km², and has the second highest GDP, with US\$14.7 trillion as of 2020 (World Bank, 2022). China is Brazil's minor competitor in the exports of soybean meal and raw sugar and is the main destination of Brazil's exports (Simoes and Hidalgo, 2011; USDA, 2022, 2021).

China is well-suited to railway transportation due to its extension and to its economy depending heavily on bulk products such as coal, metallurgical coke, metal ores, iron, steel, petroleum products, grain, and fertilizers. The average freight distance was 707 km in 2015, which is high by world standards, and China is the second largest freight carrier (in TKU, after the United States' Class I system⁸) and the largest passenger carrier (in passenger-km) in the world. However, China's market share of railway freight transportation reduced from 60% in 1990 to 18% in 2016. Among the main reasons, traffic of products other than coal and grains was actively discouraged for several decades, as freight traffic was limited to the rail capacity minus passenger traffic. The regulation of rail tariffs' prohibits tailored customer offerings based on willingness to pay. In addition, China is lacking in intermodal connectivity infrastructure for rail (on-dock rail capabilities, warehouses, access to ports, etc.), particularly container transportation (Chen et al., 2020; Transport and ICT, 2017).

Seeking to reduce carbon emissions from the road transportation sector, China started a radical modal shift policy in 2016. Its initiatives include control of overload and over clearance vehicles on road transportation, prohibition of road mode for coal, incentive modal shift from road to rail, and development of railways and intermodal transportation. The implementation of these policies resulted in an increase of more than 25% in the cost of long-distance road mode, as the construction of railways and supporting facilities is still in progress (Chen et al., 2020).

Data from the Ministry of Transportation of China showed that the average CO₂ emissions per workload of road transportation is 3.4 to 4.6 times higher than that of railway mode, and that the total CO₂ emissions of road transportation is 7.9 to 10.5 times higher than that of

⁸ "According to the Association of American Railroads, Class I railroads had a minimum operating revenue of \$489.94 million in 2018 (the latest year for which data are available)" (U.S. Department of Transportation, 2020).

railway mode. In the last few decades, the capacity shortage of some railway corridors led to hundreds of millions of tonnes of bulk freight, such as coal, to be transported on roads through long distances. The new high-speed railway network attracted some passengers, freeing railway capacity for freight transportation; however, there is little capacity surplus, especially in the coal transportation corridors. The average railway load is around 23 million tonnes per kilometer per year, which is higher than the load of most countries, and some railway corridors transport much more than the average load (Lin et al., 2017).

China is the only country in the world going through an intense railway network expansion. It was the last very large country to start building its national railway system in the 1950s, when other countries' systems have already been formed. By 2017, it already accounted for almost half of all the high-speed rail lines in the world. The railway reform was concentrated on a heavily centralized administration and on state-financed programs, combined with a network of state-sponsored railway institutes, specialist universities, testing facilities, and laboratories. It resulted in the implementation of value-adding railway technologies in construction, maintenance, operations, and management, as well as the adoption of international best practices and the creation of technologies and processes to solve China's specific operating challenges (Transport and ICT, 2017).

The sector is governed by the 1991 Railway Law that permits and encompasses four types of railways: state railways (administered by the Ministry of Transportation), local railways (managed by local governments), industrial railways (providing their own rail transportation services), and private railways sidings (branch railway lines, connecting to another railway lines). By 2015, there were 121,000 km of railways, with 50% double tracked and more than 60% electrified. The government target is to reach 175,000 route-km by 2025, with the construction of twelve new lines that will improve rail connectivity and stimulate economic growth of the poorest regions of China. The railway network also includes high-capacity coal transportation corridors based on the ten major coalfields, with an annual transportation capacity of 2.0 billion tonnes by 2020. The major container routes will be upgraded to allow double-stack container trains (Transport and ICT, 2017).

There is the state-owned and operated enterprise (SOE), China Railway, with more than 80% of market share. The lack of competitive pressure leads to inflexible operations, higher freight rates, and poor service level, reducing the railway's attractiveness. In addition, China Railway has been using its market power in network connections, line capacity allocation, revenue distribution, and access charge to prevent new entrants. These discriminations raise the entry barriers and discourage private investors and entities of joining the railway freight market, which would reduce costs and improve service quality (Chen et al., 2020). Since 1990, the Chinese government has

pursued reforms to improve the railway sector organization and productivity, such as the 2008 policy stating that all new and upgraded lines must be done on a joint venture basis, to reduce the debt accruing to the Ministry of Railway. There has been over 80 joint venture railways, established with provincial governments, enterprises, and private investors (Transport and ICT, 2017).

In 2012, the YuZinOu joint venture was established to manage freight rail services between China and Europe. Since 2013, under the program “One Belt, One Road”, the China-Europe Railway Express (CR Express) transports freight from the Chinese network of container terminals to Germany, United Kingdom and other countries (Transport and ICT, 2017).

Just like the railway sector, the Chinese road network has rapidly grown since the 1990s under a centralized infrastructure spending. In 2005, the Central government took control of the highway’s strategic planning and started the 7918 Network initiative, with seven highways starting in Beijing, nine highways from North to South, and 18 highways from East to West. During the 2008 Global Financial Crisis, the government accelerated construction of infrastructure projects to stimulate the domestic economy and continues to invest in the expansion of the road network up to this day. For instance, it is beginning to connect the highway network to the “One Belt, One Road” railway network. By the end of 2020, the total road length was around 5.2 million km (with a road density of 54.15 km/100 km²), including 161,000 km of expressways (ranking number one in the world), 4.38 million km of rural roads, 912,800 highway bridges, and 21,316 highway tunnels (Insite, 2021; Zhiqiang, 2021).

The Chinese refined oil pipeline was originally built and led by large state-owned companies. The pipelines of different companies are not interconnected nor open to other companies, so refined oil transportation is only allowed between the refineries and oil depots of the same company, causing great economic and energetic loss. With the establishment of the National Pipeline Network Company (PipeChina), the pipelines of Sinopec and PetroChina, two giant petroleum companies, will no longer be managed separately. This is a step towards the interconnection of the pipeline network, which is expected to increase pipeline utilization and logistics flexibility and to reduce turnover cost, freight rates, GHG emissions, and shortage of oil depots downstream due to the shutdown of a single pipeline. Currently, the reform is in its early stages and the interconnection between pipelines is under construction (Wei et al., 2022).

China has the world’s most extensive inland waterway system with 126,300 km of navigable waterways as of 2014, although it has not been as developed as other modes. In the last few years, the government has invested in improvements to create interlinked, high-standard routes, with channel dredging, ship lifts, and new and upgraded locks and terminals for bulk and

container traffic. The main waterway route, both in China and in the world, is the Changjiang or Yangtze River, which runs from West to East and connects the inland and the coast (ADB, 2016).

Figure 5 presents China's main roads, railways, and waterways.

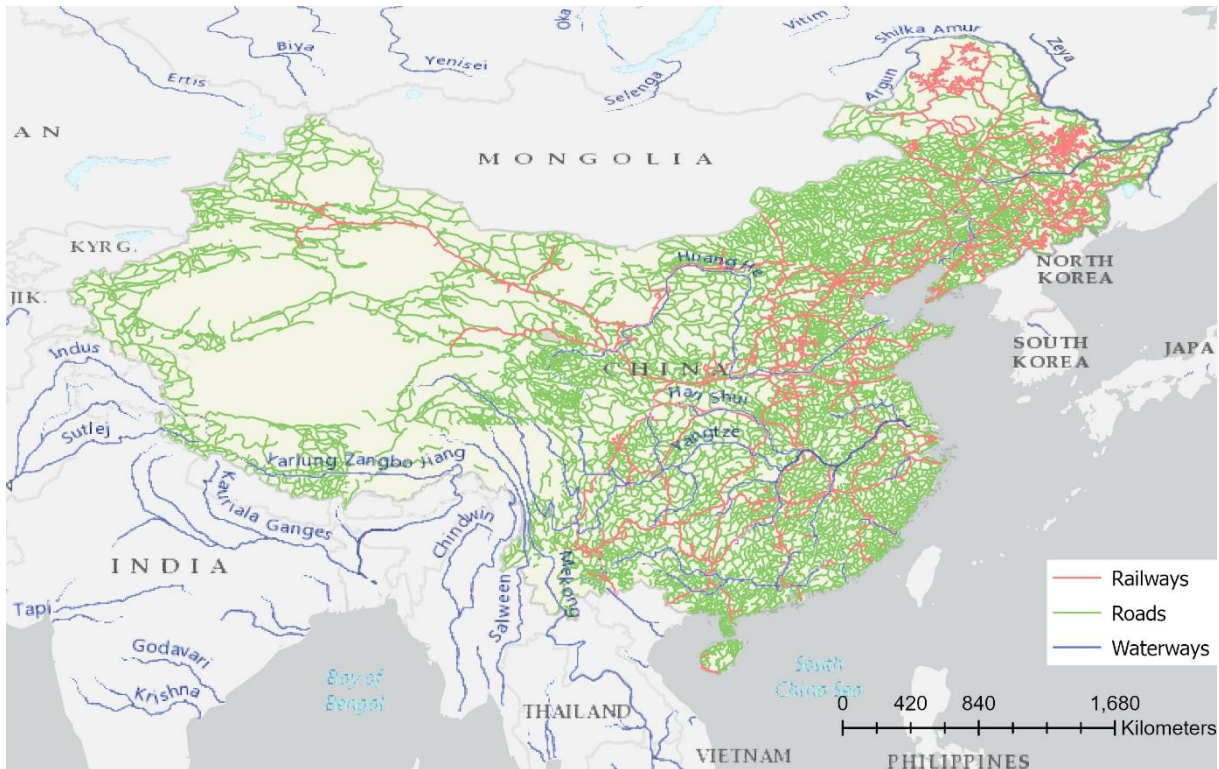


Figure 5. China's main roads, railways, and waterways.

Sources: DIVA-GIS (2023) and World Water Online (2023).

2.2.5. Canada

Canada is the second largest country in the world, with 9.9 million km², and has the ninth highest GDP, with US\$1.6 trillion as of 2020 (World Bank, 2022). Canada competes with Brazil in the exports of iron ore, crude petroleum, and sulfate chemical wood pulp, and is a minor competitor in the exports of soybean, soybean meal, and frozen bovine meat (Simoes and Hidalgo, 2011; USDA, 2022, 2021).

Canada has a vast and sparsely populated territory, facing extreme weather conditions, making a challenge to ensure the safe, secure, and efficient movement of products and passengers across the country. The transportation network consists of 38,000 lane-kilometers of highways, more than 1.13 million two-lane equivalent lane-kilometers of public roads (of which 40% are paved), 43,000 route-kilometers of railways, 18 ports and 563 port facilities, over 840,000 km of

pipelines, and 26 major and 220 minor airports (Government of Canada, 2020, 2018; Transport Canada, 2020).

Regarding the freight railways sector, it is specialized in moving heavy, bulk commodities and containerized cargo, mainly to and from the United States and the coastal ports. There are two major Class I railways: Canadian National railways, which owns 22,000 km, and Canadian Pacific, with 13,000 km. Together, they operate 19 intermodal terminals that run truck/rail and container intermodal services. Around 70 companies, including large US-based carriers such as Burlington Northern Santa Fe Railway Company and CSX Transportation Inc., are responsible for the remaining 8,000 km of railways, mostly connecting shippers of products with Class I railways, other short lines, and ports (Government of Canada, 2018; Transport Canada, 2020).

Western Canada is the country's gateway to the Asia-Pacific region. The port of Vancouver is the largest Canadian port, handling 145.5 million tonnes of traffic in 2020 in its 29 terminals. The port of Prince Rupert is the fastest growing port in Canada and offers the shortest ocean shipping route between China and North America. Both ports are connected to the Canadian National and Canadian Pacific railways, facilitating the transportation of bulk commodities from Prairie provinces to the British Columbia ports. Domestic market is attended mainly by highways and tug and barge⁹ operations (Transport Canada, 2020).

Central Canada moves cargo to and from the United States, Europe and other international markets using the Great Lakes and St. Lawrence Seaway System. It is a 3,700 km "marine" highway from the head of Lake Superior (Duluth, Minnesota) to the Atlantic Ocean (Gulf of St. Lawrence) that moves 200 million tonnes of cargo annually and can be crossed in 8.5 sailing days. The St. Lawrence Seaway is a binational partnership between the United States and Canada and consists of two sections: a 306 km stretch between Montreal and Lake Ontario, with seven locks to lift vessels 75 meters above the sea level, and the Welland Canal linking Lake Ontario to Lake Erie, with eight locks. The 15 major ports of the system are linked with more than 40 provincial and interstate highways and nearly 30 rail lines, creating a multi-modal transportation network across the continent. Bulk materials (such as iron ore, salt, and liquid petroleum), transshipments of exports and container imports are shipped from the St. Lawrence Seaway portion of the network, while grains from the Prairies are usually shipped from the port of Thunder Bay and carried to different Quebec ports for international exports (St. Lawrence Seaway Corporation, 2022; Transport Canada, 2020). Apart from the Great Lakes and St. Lawrence Seaway System, the road transportation is the main mode to move food products, manufactured and other

⁹ Tugs or tugboats are self-propelled vessels, while barges are nonself-propelled vessels (U.S. Department of Transportation, 2020).

processed goods within the Quebec City-Windsor corridor and to the United States region around the Great Lakes (Transport Canada, 2020).

In Eastern Canada, marine ports connect the region to international and domestic markets. Its main exporting products include petroleum and seafood products. The port of Halifax is one of the few ports on the North American East coast that can handle post-Panamax container ships, being North America's closest point of ice-free access to Europe and Asia via the Suez Canal. The port of Saint John (New Brunswick) is important for processing, refining, and shipping crude oil. There is a single Class I railway providing freight services to and from Central Canada to Halifax and short line railways provide feeder services in Nova Scotia and New Brunswick (Transport Canada, 2020).

Figure 6 shows Canada main road and railway networks, while Figure 7 presents the country's main ports and the Great Lakes and St. Lawrence Seaway System.



Figure 6. Canada's road and railway network.

Source: Open Canada (2023a, 2023b).



Figure 7. Canada’s main ports and the Great Lakes and St. Lawrence Seaway System.

Source: Transport Canada (2020).

The government of Canada is currently implementing the strategic plan “Transportation 2030”, which has the objective of promoting a safe, secure, green, and integrative transportation system. Among the ongoing initiatives in 2020, there is the national Oceans Protection Plan to protect Canada’s marine environment and coasts, and the National Trade Corridors Fund that committed the fund’s initial US\$1.4 billion¹⁰ allocation to 89 transportation infrastructure projects to strengthen and increase the efficiency of transportation corridors. The Canadian government also released the climate plan “A Healthy Environment and a Healthy Economy”, with actions and commitments to meet and exceed its 2030 Paris Agreement emissions reduction target and achieve net-zero emissions by 2050 (Transport Canada, 2020).

2.2.6. Russian Federation

The Russian Federation is the largest country in the world, with 17.1 million km², and has the eleventh highest GDP, with US\$1.5 trillion as of 2020 (World Bank, 2022). Russia competes with Brazil in the exports of crude petroleum and is a small competitor in the exports of raw sugar (Simoes and Hidalgo, 2011; USDA, 2022, 2021).

¹⁰ The values were converted from Canadian Dollar to US Dollar, using the CAD/USD 2020 average exchange rate of 0.7461 (Bank of Canada, 2022).

Like Canada, Russia faces a combination of long distances, inhospitable climates, and interconnectivity problems, with the complication of having a population more sparsely distributed. Only one in every eight Russians live in the country's three largest cities, as opposed to two out of three Canadians (Ferris and Connolly, 2020). However, Canada has managed to build a transportation network that connects even the most remote areas of the country and provides an efficient and competitive service to move goods, while Russia Eastern region lacks the necessary transportation infrastructure to link with the other regions and move its products.

As expected, Russia's transportation network is one of the most extensive in the world, with 87,000 km of railways, 745,000 km of paved roads (with 37,000 km of public roads of federal importance meeting regulatory requirements), 70,000 km of oil products pipelines, 140,000 km of gas pipelines, and 115,000 km of inland waterways (Kazak et al., 2020). However, the transportation network is concentrated in the Western and Central regions (Bardal and Sigitova, 2020). In addition, the transportation system faces currently low technical production level and deterioration of most vehicles, leading to a decrease in work safety, overloaded port systems, an insufficient quantity of bridges capable of accepting increases in cargo, and challenging seasonal weather conditions (Ferris and Connolly, 2020; Kazak et al., 2020)

Railway is the most important transportation mode in Russia, due to the long distances between the main agricultural and industrial centers from the seaports, the lack of inland waterways in the East-West direction, and the varied terrain. Currently, the holding Open Joint Stock Company (OJSC) "Russian Railways" is the main owner of Russia's public infrastructure and is the only carrier in freight traffic, tending to win most state contracts for railways. This lack of competition discourages private investors, even though the Target Market Model is expected to create competition "on the route" or "for the route" between private carriers. The length of the Russian railway network has practically not changed in the past 25 years and the technical equipment is outdated and aging due to the low level of investment. Hence, the network is facing 8,000 km of bottlenecks (30% of the main cargo-intensive areas of the network) because of a significant increase in the volume of laden and empty cars flows. There are seven regions of the Russian Federation with no railways, and 25% of the railways in the central regions operate in overload mode (Ferris and Connolly, 2020; Kurenkov et al., 2019).

In the last few years, there has been a shift from rail to road freight transportation, due to an increase in efficiency of the road mode. Railways used to be more competitive for distances over 500 km, and now this distance has grown to 700-750 km. In addition, certain regions of Russia are only safely accessed by road. There has also been an increase in air transportation, despite the outdated fleet of vehicles (Kazak et al., 2020).

The public road network consists of federal road network with 55,000 km; regional roads with 472,000 km; and local roads with 530,000 km. In the past 20 years, there was a slight increase in federal roads, a decrease in regional roads, and an increase on local roads, especially access roads to individual rural settlements. On federal roads, 9% of its extension withstand a permissible load of 11.5 tonnes per axle and 54%, 10 tonnes per axle. On regional roads, 30% endure 10 tonnes per axle and on local roads, only 0.5% (Kurenkov et al., 2019). In addition, 22% of public roads of federal importance were serving traffic in overload mode (Kazak et al., 2020), which can fill the roads with potholes, reducing speed and increasing traffic.

Around 30% of the 2,120 bridges of the public road network are in unsatisfactory technical conditions (Kurenkov et al., 2019), despite being mostly necessary in a country with more than 2.8 million rivers. Several cities cannot be accessed directly because there is no road or rail bridges, which also negatively impacts cross-border trade with China. Currently there are only 42,000 bridges in Russia (Ferris and Connolly, 2020).

The port of Saint Petersburg is Russia's leading container port. Just like other Russian ports, it suffers from underdeveloped port infrastructure, with the surrounding area facing road congestion, poor operational condition of roads, and inefficient traffic management, causing delays and increasing costs (Ferris and Connolly, 2020; Kotikov, 2015). Russia has been trying to develop the Northern Sea Route, which is the shortest sea way between Europe and Asia. It goes through the seas of the Arctic Ocean for around 4,600 km and can lessen journey times in around 10 days, benefitting especially products with shorter shelf lives (Ferris and Connolly, 2020; Katysheva, 2018).

The Russian government intends to establish the Russian Far East (RFE) region, which encompasses 41% of its territory, as a trade and investment hub linking Asia with Europe. Ever since Russia's annexation of Crimea in 2014, the military intervention in Eastern Ukraine, and the following economic sanctions and weakened relations with the Western countries, the Asian markets and investments have become more important to Russia. China, Japan, India, and South Korea are large importers of crude oil, natural gas, coal, and precious metals, all of which have significant reserves in RFE (Ferris and Connolly, 2020).

Currently, the Russian Eastern region suffers from poor connections between its roads, railways, airports, ports, and maritime infrastructure. Around 15 million people (10% of the population) are cut off from transportation networks during certain seasons, and more than 46,000 settlements in the RFE and Siberia are not connected to the broader road system and to neighboring countries (Ferris and Connolly, 2020).

The RFE region requires sustained and systematic improvements to its transport networks, mainly railways, bridges, and ports, to attract the foreign investment needed to enhance freight capacity and support export growth. Until now, only the energy transportation infrastructure has made progress, with the ESPO oil pipeline and the Power of Siberia gas pipeline (Ferris and Connolly, 2020). The Russian government launched a socio-economic development program aiming to solve transportation problems until 2030 (Kazak et al., 2020). As its economy has performed relatively poorly since 2013, the need for substantial foreign investments in critical infrastructure has increased, but the government is concerned that it might make the country subject to foreign power. In addition, investments in the RFE are a high-risk venture for foreign investors, due to the prioritization of political initiatives (such as the Crimea Bridge, the Winter Olympics in Sochi in 2014, and the FIFA World Cup in 2018) over practical projects that would link up Russia's rural regions and promote economic development. There is a lack of feasibility studies and of a government strategy to coordinate infrastructure policy and development. Furthermore, the systemic corruption has siphoned public funds from major construction projects in the RFE and has forced the abandonment of many large-scale infrastructure projects before their completion. There is local resentment towards Asian partners, especially China, and there are political differences between Russia and other Asian countries. On top of that, there are only three organizations in Russia (based on Moscow and Saint Petersburg) conducting research on road and railway construction, which limits the development of innovative construction materials, configuration of infrastructure in remote territories, and generates a knowledge gap (Ferris and Connolly, 2020).

As Russia invaded Ukraine in February 2022, the Western governments imposed financial and technological sanctions on the country, resulting on a sharp drop in the imports of Western equipment and technology and on a steep economic decline. Consequently, domestic companies suspended indefinitely large-scale investment projects and foreign companies left Russia, while China became an even more important partner for trade and investment (Aronova, 2022).

Figure 8 presents Russian road, railway, and waterway networks.



Figure 8. Russia's road, railway, and waterway networks.

Sources: DIVA-GIS (2023) and World Water Online (2023).

2.2.7. Australia

Australia is the sixth largest country in the world, with 7.7 million km², and has the thirteenth highest GDP, with US\$1.3 trillion as of 2020 (World Bank, 2022). Australia competes with Brazil in the exports of iron ore and frozen bovine meat, and is a minor competitor in the exports of raw sugar (Simoes and Hidalgo, 2011; USDA, 2022, 2021).

In 2021, the Australian total road length was of 875,000 km and the open railway network comprised 33,000 route km. Cabotage mostly carries bulk commodities (70% of domestic movements) such as aluminum ores, iron ore and petroleum between major domestic centers (BITRE, 2021, 2014).

The federal and state governments, which are the owners of most of the rail network, performed an extensive reform in the Australian railway industry in the 1990s, establishing open access to the railway network and creating the Australia Rail Track Corporation (ARTC). All freight train operators are independent private companies. Currently, the ARTC is responsible for maintaining, managing, and implementing major investments projects in the 8,500 km interstate railway network of the federal line and of five states, plus the Hunter Valley export coal lines in New South Wales (NSW). Most of the ARTC network is single tracked. In 2018, ARTC began the construction of an inland rail link of 1,700 km between Melbourne and Brisbane via regional Victoria, New South Wales, and Queensland, with a new alignment and an upgraded rail track. This new rail line will reduce travel times for freight transportation between these regions (and their respective ports) as it bypasses the more congested Sydney rail network. Its construction is forecasted to be concluded by 2024-25 (Deloitte Access Economics, 2019; Transport and ICT, 2017).

The ARTC operates under access undertakings on the interstate network. The price setting follows a “negotiate-arbitrate” model and floor and ceiling limits. As the government funds most major investments and upgrades, the ARTC can set access charges that are low enough to cover only recurrent expenses and renewals and that are competitive with the price charged by the competing road transportation (Transport and ICT, 2017).

Despite of all rail networks having open access regimes, there is limited competition among rail providers in Australia, mainly due to high entry and high investment costs. In some states, competition is even more restricted as there are different rail gauges operating across networks, which add costs in operations across multiple states. There is a standard gauge interstate coastal network linking Brisbane, Sydney, Melbourne, Adelaide, and Perth that was only available in 1995; a standard gauge rail line from Port Augusta to Darwin; several regional state-based networks with different gauges; and some privately-owned rail lines linking regional mines with ports (mostly in northern Australia) (Deloitte Access Economics, 2019; Transport and ICT, 2017).

The regional rail network, which is almost 100 years old in many states, is losing transported volume to road mode. It mainly transports grains, which have a seasonal nature, resulting in large variations in transported volume from year to year. Even if the regional lines only move little or no grain for a period, they require constant maintenance. However, the rail access fees paid by rolling stock operators only cover about 1% of the total maintenance costs, resulting in maintenance deficit and lack of investment in rail loading and track infrastructure for this network. In the last few years, New South Wales’s and Victoria’s governments have launched initiatives to fund maintenance and upgrade of the regional rail network, but uncertainty remains regarding the future of regional lines in most states. There are some regions (such as Western Australia) already closing rail lines due to low freight volumes and lack of funding (Deloitte Access Economics, 2019).

In Australia, rail is mostly freight oriented. The bulk freight comprises mainly iron ore, coal, and grains and travels 50 to 500 km from the interior of the country to the exporting ports. The long-haul intermodal/general freight travels 1,000 to 4,000 km between the state capitals, with rail operators usually being wholesalers in this market (Transport and ICT, 2017). In the last few years, traffic on the long-haul East-West routes and on the Hunter Valley lines has grown steadily, while it has been stable at best in the North-South corridors and in the three shorter East-West corridors. Railways have lost freight market share to roads due to rail investment delays, improved roads and use of larger vehicles (Transport and ICT, 2017). In 2015-16, 68% of bulk freight was moved by rail (in %TKM), 13% by road, and 18% by cabotage. The non-bulk freight transported by rail was only 19% (in %TKM), with 77% by road and 4% by cabotage (BITRE, 2021).

There was an increase in the size of articulated trucks and in the number of larger truck combinations, more than doubling the average load carried by vehicle, and increasing road transportation productivity. On the other hand, only 44% of the total road length was paved on 2015 and there is a maintenance deficit for most local rural roads in all states, which serves as a first mile entry point onto the regional road network. In addition, many of these local roads cannot accommodate higher productivity freight vehicles, as the upgrade cost is often prohibitive (BITRE, 2021; Deloitte Access Economics, 2019). Heavy vehicles must pay road user charges to compensate marginal costs on the system such as operating costs, road provision, repairs, maintenance costs, and land acquisition costs. However, traffic control, enforcement costs, cost of historically provided assets, and financing costs are excluded, generating discussion about these being a fair contribution to road construction and maintenance costs (Transport and ICT, 2017).

Logistics are the largest cost in the production of many agricultural industries in Australia, reaching up to 48.5% of farm-gate cost. Road is the dominant transportation mode for livestock and meat, dairy, grains, chicken meat, horticulture products, cotton, and sugarcane (Deloitte Access Economics, 2019).

Around two thirds of Australia's grain production are exported, so the main freight routes are from grain producing areas to ports with bulk loading capacity. Major grain traders and companies own and operate most of the long-established bulk grain storage network, which allow grains to be transported from storage to exporting ports around the country by rail. In the domestic market, only a reduced number of flour and stockfeed mills have access to rail facilities and receive grain moved in bulk form by rail. The average annual transportation costs for winter grains (wheat, barley, and oats) were estimated at US\$2,092 million¹¹ (US\$1,652 million in road and US\$440 million in rail modes), while farm freight costs were 27.5% of the gross farm production (Deloitte Access Economics, 2019).

In Western Australia, most canola (an annual average of 10-12 million tonnes) is transported in bulk from up country storage facilities to exporting ports by rail. The Western Australian rail network is owned by the government of Western Australia and is under a long-term operating lease to Arc Infrastructure. Around 2,400 kilometers (44%) of this rail network is dedicated exclusively to transport grains, and contains 16, 19 and 21 plus tonnes/axle load capable rail, with both standard gauge and narrow-gauge track. In 2014, Arc Infrastructure ceased operations of nearly 500 km of track due to low competitiveness with road transport, restricting modal's options in these regions. (Deloitte Access Economics, 2019).

¹¹ The freight values presented in section 2.2.7 were converted from Australian Dollar to US Dollar, using the AUD /USD 2017 average exchange rate of 0.7692 (RBA, 2022).

Queensland produces 95% of Australia's sugarcane. It is often transported from farms to mills by cane railway networks and rolling stock. The annual average sugarcane transport costs and other fees was estimated at US\$40.1 million by road and US\$7.65 million by rail, although it does not consider road transport to domestic market and rail transport from paddock to mill. Farm road freight costs were 2.1% of the gross farm production (Deloitte Access Economics, 2019).

Figure 9 shows the Australian main road and rail networks.



Figure 9. Australia's main road and rail networks.

Source: Geoscience Australia (2023).

2.2.8. Comparison among countries

For grains supply chain, Canada has higher land transportation cost, higher farm storage cost, lower port cost and lower labor cost than Australia. This cost variation reflects the differences between their supply chains'. In Australia, there are multiple supply chains operating within each state, with grains being stored in centralized bulk storage units following harvest. Afterwards, there

is the possibility to choose between road or rail transportation to reach multiple exporting ports. In Canada, grains are stored on farm and transported directly for shipping, traveling longer distances (in average, six times higher than in Australia) to reach a few exporting ports by rail transportation provided by the two major rail companies. In addition, Australia's rail network and rail operation standards are more efficient than Canada, whereas fuel cost and the quality of road infrastructure are similar. On the other hand, Russia has lower costs than Australia and Canada, mainly due to its currency being relatively weaker, although its roads and ports have a lower quality. Russia transports grains through long distances by its extensive rail network, using the more efficient road mode for journeys of less than 500 km. Australia has a storage and handling infrastructure of better quality, which reflects in a higher cost and in grains of higher quality, while Russia has a limited need for airtight storage due to temperatures in most grain-producing regions being low enough to kill most grain insect pests (Deloitte Access Economics, 2019).

Regarding overall transportation infrastructure, Brazil's can be considered inadequate. The World Economic Forum (WEF) has been publishing the Global Competitiveness Report for almost 40 years. Among its pillars, there is one dedicated to infrastructure. Up until 2017, there were quality indicators for overall infrastructure, roads, railroad infrastructure, port infrastructure, and air transportation infrastructure. Their value is derived from the Executive Opinion Survey, answered in 2017 by 12,775 business executives in 133 countries. To determine the quality of each mode's infrastructure, they answered what is the quality (extensiveness and condition) of each system in their country, from 1 = extremely poor (among the worst in the world) to 7 = extremely good (among the best in the world) (Schwab, 2017). Table 5 shows the results for 2017 for the analyzed countries, out of a total of 137 countries. France, the biggest country in extension, and Germany, the highest populated, represent the European Union.

Table 5. Ranking and value of quality of transportation infrastructure indicators for the analyzed countries (2016–17 weighted average).

Country	Ranking (Value) - Quality of transportation infrastructure indicators			
	Overall infrastructure	Roads	Railroad infrastructure	Port infrastructure
USA	10 (5.9)	10 (5.7)	10 (5.5)	9 (5.8)
France	8 (6.1)	7 (6.0)	5 (5.8)	27 (5.1)
Germany	12 (5.7)	15 (5.5)	9 (5.5)	18 (5.5)
Canada	23 (5.2)	22 (5.4)	16 (4.9)	19 (5.4)
Australia	39 (4.7)	35 (4.8)	35 (4.1)	35 (4.9)
China	47 (4.5)	42 (4.6)	17 (4.8)	49 (4.6)
Russia	74 (4.0)	114 (2.9)	23 (4.5)	66 (4.2)
Brazil	108 (3.1)	103 (3.1)	88 (2.0)	106 (3.1)

Source: Schwab (2017).

From 2018 onwards, the quality of railroad, port, and air transportation infrastructure indicators were replaced by efficiency of train, air transportation, and seaport services indicators, with the addition of road connectivity, railroad density, airport connectivity, and liner shipping connectivity indicators. The results for 2019 for the analyzed countries are presented in Table 6, out of a total of 141 countries (Schwab, 2019).

Table 6. Ranking and value of transportation infrastructure indicators for the analyzed countries (2018–2019 weighted average or most recent period available).

Country	Ranking (Value) - Transportation infrastructure indicators					
	Road connectivity (0-100)	Quality of road infrastructure (1-7)	Railroad density (km/1,000 km ²)	Efficiency of train services (1-7)	Liner shipping connectivity (0-100)	Efficiency of seaport services (1-7)
Germany	11 (95.1)	22 (5.3)	7 (95.9)	16 (4.9)	7 (97.1)	18 (5.2)
France	6 (96.6)	18 (5.4)	17 (53.4)	15 (5.0)	12 (84.0)	20 (5.2)
USA	1 (100.0)	17 (5.5)	48 (16.5)	12 (5.2)	8 (96.7)	10 (5.6)
Canada	4 (98.7)	30 (5.0)	68 (5.3)	27 (4.5)	32 (51.7)	26 (5.1)
China	10 (95.7)	45 (4.6)	61 (7.2)	24 (4.5)	1 (187.8)	52 (4.5)
Australia	13 (94.5)	34 (4.9)	98 (1.1)	29 (4.4)	56 (31.0)	37 (4.8)
Russia	41 (85.7)	99 (3.5)	69 (5.2)	17 (4.9)	43 (40.4)	47 (4.7)
Brazil	69 (76.1)	116 (3.0)	78 (3.6)	86 (2.5)	48 (38.2)	104 (3.2)

Source: Schwab (2019).

In 2017, Brazil not only was the lowest ranking country among the analyzed countries but was also well below them. In 2019, Brazil showed a better performance with the new set of indicators but remained the lowest ranking country among the analyzed countries. It shows that Brazil has relatively well-connected transportation networks, but with poor quality or efficiency.

The results were better in the World Bank's Logistics Performance Index (LPI) with Brazil ranking in the upper half, almost 30 positions ahead of Russia (Arvis et al., 2018). The LPI "tries to capture how logistically accessible, or how well connected to the physical internet of global logistics, a country is. It includes several dimensions" (Arvis et al., 2018, p. 7):

1. The efficiency of customs and border management clearance.
2. The quality of trade- and transport-related infrastructure.
3. The ease of arranging competitively priced international shipments.
4. The competence and quality of logistics services.
5. The ability to track and trace consignments.
6. The frequency with which shipments reach consignees within the scheduled or expected delivery time. (Arvis et al., 2018, p. 8).

The LPI data are collected through a worldwide survey of logistics professionals, who answers questions related to how easy or how difficult is the experience of trading logistics in eight preselected countries (Arvis et al., 2018). The aggregated results for 2012-2018 for the analyzed countries are presented in Table 7, out of a total of 167 countries.

Table 7. Aggregated international LPI results across four editions (2012, 2014, 2016, and 2018) for the analyzed countries.

Country	Ranking (Score) - Aggregated international LPI						
	Mean LPI	Customs	Infrastructu re	Internatio- nal shipments	Logistics quality and competence	Tracking and tracing	Timeliness
Germany	1 (4.19)	1 (4.09)	1 (4.38)	4 (3.83)	1 (4.26)	1 (4.22)	1 (4.40)
USA	10 (3.92)	11 (3.76)	6 (4.10)	23 (3.54)	11 (3.93)	3 (4.13)	16 (4.14)
France	15 (3.86)	18 (3.63)	12 (4.00)	15 (3.60)	17 (3.82)	12 (3.99)	14 (4.17)
Canada	17 (3.81)	15 (3.70)	16 (3.91)	28 (3.45)	13 (3.90)	15 (3.91)	21 (4.03)
Australia	19 (3.77)	10 (3.76)	15 (3.92)	31 (3.40)	19 (3.76)	19 (3.83)	22 (4.00)
China	27 (3.60)	30 (3.28)	24 (3.73)	18 (3.57)	27 (3.58)	28 (3.63)	29 (3.86)
Brazil	56 (3.02)	85 (2.52)	51 (2.99)	65 (2.89)	46 (3.10)	49 (3.17)	53 (3.47)
Russia	85 (2.69)	131 (2.25)	73 (2.64)	105 (2.59)	73 (2.74)	88 (2.67)	74 (3.23)

Source: Arvis et al. (2018).

3. TRANSPORTATION PLANNING

The first and major determinant of modal choice is the availability of transportation infrastructures, which starts with a suitable transportation planning. This thesis' proposed model designs a new railway to link the Brazilian Center-West and South regions; selects the location of warehouses that need to increase the static capacity and determine the necessary volume; calculate the most used transportation infrastructures; and find the most promising entry points to imported products. To achieve satisfactory results and to guarantee that this thesis contributes to the literature, this chapter presents a literature review about transportation planning, with focus on freight transportation.

Hence, the following sections show relevant studies that focused on the strategic level of freight transportation planning and design (section 3.1), that used GIS to enhance the solution method (section 3.2), and that applied these methods on Brazil (section 3.3). These studies are the basis for the method proposed in this thesis (chapter 4).

3.1. Freight transportation planning and design

Freight transportation planning is classified into three levels: strategic, tactical, and operational (Crainic and Laporte, 1997; Steadieseifi et al., 2014). The strategic planning problem is the long-term level and considers the investment decisions on the network infrastructure, such as building new lines, improving existing lines, and locating main facilities (Crainic and Laporte, 1997; Steadieseifi et al., 2014).

In the tactical planning problem (medium term), the objective is to efficiently use the available infrastructure to plan the orders' itineraries and frequency by choosing services and related transportation modes, improving the performance of the entire system. This problem is solved by two groups of models: the Network Flow Planning (NFP), that addresses the orders (commodities) movement throughout the network, and the Service Network Design (SND), which includes the choice of transportation services and modes to move those commodities (Crainic and Laporte, 1997; Steadieseifi et al., 2014).

The last level is the operational planning (short term), that includes scheduling of services and maintenance activities, routing, and resource allocation and considers real-time requirements of operators, carriers, and shippers (Crainic and Laporte, 1997; Steadieseifi et al., 2014).

Kosijer et al. (2012) presented a route selection methodology based on multicriteria decision-making to solve the railway route planning and design problem. The first level consists of

defining basic program requirements, i.e., horizontal, vertical, and structural elements of the route, traction system and transportation organization scheme, and a map of route-related limitations. In the second level, the designer finds a set of alternative route solutions by changing technical route elements and by adapting the solution to the physical setting, terrain, geological, and hydrological conditions. The third level consists of eliminating the alternatives that do not meet the parameters. The fourth level is the selection of the appropriate criteria to evaluate the alternative solutions, which in this study are construction, operation and maintenance costs, capacity, and effects on physical development and on living environment. Then, in the fifth level these solutions are evaluated based on the selected criteria. The sixth level is the ranking of the alternative solutions, and the last level analyzes and selects the best solution using the VIKOR method. Given the conflicting nature of the criteria, the method selects the compromise solution, which is the best ranked alternative with "sufficient advantage" over the next alternative and "sufficiently stable" position when changing the weight coefficients in different scenarios. The methodology was tested on the design of the double track railway line between Inđija and Novi Sad (Serbia).

Arnold et al. (2004) formulated a linear 0-1 program solved by a heuristic to optimally locate rail/road intermodal terminals for freight transportation that minimizes total transportation cost. In the formulation, the terminal is considered as an arc in a graph and not as a vertex, thus reducing the number of decision variables in a sparse network. In addition, the formulation allows more than two transfers between origin and destination. Due to the size of real-world intermodal transportation problems, it is not expected to find an exact solution within a reasonable time limit, therefore the heuristic Intermodal Terminals Location Simulation System (ITLSS) is proposed. The model is applied to the Iberian Peninsula and five scenarios are evaluated, showing that the modal split is extremely sensitive to the relative cost of rail and has minor impact due to new or relocated terminals.

Yamada et al. (2009) proposed a bilevel model to solve the investment planning problem, which consists of identifying and choosing a proper set of actions to develop multimodal freight transportation networks. The actions include improving existing infrastructure or construction of new roads, railways, sea links, and freight terminals. The problem is modeled as a discrete network design problem (DNDP), where the actions are characterized by the addition of new links or by the improvement of existing links. This type of problem also involves a mathematical problem with equilibrium constraints (MPEC). The model incorporates traffic and freight flows on the transportation network and can be represented as a leader-follower game, with the transportation planning departments as leaders and the transportation network users as followers.

In Yamada et al. (2009), the lower level incorporates the multimodal multiclass user equilibrium traffic assignment using a modal split assignment model. The aggregate approach was chosen because of the available interregional data from Philippines, thus the influence of shipper-carrier behavior or their interaction in the freight transportation decision is not explicitly considered in this model. This model treats freight and passengers as multiclass users, and the modal split and route choice happens simultaneously by converting the multimodal network into a unimodal abstract network. The freight movement within terminals considers loading/unloading, storage, and administrative processes. The lower-level problem utilizes user equilibrium conditions with a non-separable and asymmetric Jacobian matrix cost function among user types. The upper level approximately optimizes the selection of actions and is considered a combinatorial optimization problem. Thus, it is solved with a metaheuristic-based procedure called genetic local search (GLS), that is a combination of the genetic algorithm (GA) and the local search. The objective function is the benefit-cost ratio (BCR) between the reduced total freight cost and the investment and operational costs of implementing the selected actions.

The authors compared the proposed method with two GA-based procedures, three Tabu Search-based (TS) procedures and the random search method (RSM) in a small transportation network in West Java (Indonesia), with the GLS consistently providing better performance in reasonable computation times. Then the model was applied to a larger transportation network in Philippines consisting of 424 nodes (331 O-D pairs for freight and 340 O-D pairs for passengers) and 1,871 links representing national, provincial, and toll roads, railways, and port-to-port sea routes. The model adequately represented major transportation flows and selected road widening actions that led to an effective design of the multimodal freight transportation network.

Maia and Couto (2013) proposed a strategic planning freight traffic assignment model to improve rail networks on a regional and national level. It considers road and rail transportation modes and contemplates two types of cargo: intermodal cargo, which is generally transported in containers and can change modes at intermodal terminals, and general cargo that represents all other cargo. The objective function is to minimize total generalized costs and carbon dioxide (CO₂) emissions. The model includes links that represent road and rail networks, intermodal terminals, congested rail nodes, and connector links between the road network and the centroids representing traffic-generating regions. It is possible to construct new links or improve the existing ones. The shortest path between any pair of nodes is calculated with the Floyd–Warshall algorithm with path reconstruction. The assignment process depends on the cargo type. General cargo may use only one transportation mode and the traffic distribution between the two modes is defined through a stochastic-multiflow technique, implemented with a logit function that calculates the percentage of

traffic that uses each mode. Intermodal cargo traffic is assigned through an all-or-nothing technique to the least-costly path, which may include both road and rail modes. The model considers capacity limits on rail links and at intermodal terminals. The physical capacity of each rail link is represented in the network by congested rail nodes with a limited capacity, equal to the total capacity minus the flow of passenger trains. To ensure the capacity constraints, the authors did not use an equilibrium model. Instead, the total freight flow is gradually inserted into the network and when the capacity of a link is exceeded, it is removed from the network in subsequent iterations. The optimization process comprises a greedy algorithm that creates an initial solution, a local search heuristic that searches for better solutions near the initial solution, and a shaking process that avoid local optimum by jumping to a different point in the search space. The method was applied to two fictional networks, producing satisfactory results.

Yamada and Febri (2015) developed a discrete optimization model for transportation network (TN) within the framework of mathematical programs with equilibrium constraints (MPEC) to solve the multimodal freight transportation network development problem. This investment planning problem consists of finding and choosing a fitting set of new links to be added or existing links to be renovated. The MPEC's lower level is built with embedded supply chain–multimodal transportation super network equilibrium (SC-MT-SNE) in the constraints and calculates the quantities and the prices of transported products between supply chain networks (SCN) entities (manufacturers, wholesalers, retailers, freight carriers, demand markets, and TN users), and the traffic conditions on the TN, thus also considering passenger transportation. The lower-level model explores the effects of road network traffic on the entities' actions and vice versa, endogenously determining transportation costs. The multimodal TN considers road, rail, and water modes, and transshipment and transfer terminals between them. The model's upper level identifies the combination of TN improvements that approximately maximizes the SCN-related benefit-cost ratio through a modified version of the probability-based discrete binary particle swarm optimization (MPBPSO) algorithm. Solutions found in each level impact the other. The SCN-related benefit-cost ratio is the ratio of the increased total surplus on the SCNs and the investment/operation costs of the selected actions.

The authors assessed the model on a small super network, to determine the best MPBPSO parameter values, and on a larger-sized hypothetical super network, composed of two urban areas with roads and an interurban multimodal TN with roads, railways, and sea links, adding up to 20 nodes, 66 existing and 16 planned links, 8 construction and 31 renovation actions. There are two kinds of products, and each SCN has two manufacturers, two wholesalers, two retailers, four demand markets, and one freight carrier. The functional forms and parameters values were

calibrated with actual Japanese data and the authors showed that the MPBPSO has a better performance than other heuristics. However, the larger-sized hypothetical super network is much smaller than a realistic large-sized problem. The hindrance is the computational time, especially for estimating traffic flow in the lower-level SC-MT-SNE.

Alireza Seyedvakili et al. (2020) developed a mixed integer model for the multiperiod railway network design problem. The model considers new lines construction, existing lines improvement and maintenance projects, the available budget, and the O-D demand matrix for each period, and block and technical capacities. It determines the progress rate of each selected project based on budget and effect on the network and manages unmet demand in different periods. The objective function is to minimize total rail operation cost (railway track, rolling stock maintenance, operation, safety, environmental, pollution, and energy consumption costs) and total lost demand cost. The suggested model was implemented in the Iranian railway network and was solved by an exact method, showing the model's efficiency.

The aforementioned studies are summarized in Table 8. In common, they all search for the best infrastructure projects, whether it is the construction of a new line or of a new intermodal terminal, or the improvement of an existing line that optimize a freight transportation network. However, they consider the projects as inputs and do not propose and evaluate if there is a better alternative to these existing projects. In addition, each of these studies has a particular characteristic that is worthy of using as a reference in future papers.

Table 8. Summary of studies on freight transportation planning and design.

Author(s)	Year	Problem	Method	Characteristics	Test case
Kosijer et al.	2012	Railway route planning and design	Multi-level route selection methodology based on multicriteria decision-making.	Selects the best ranked solution with "sufficient advantage" over the next alternative and "sufficiently stable" position.	Design of the double track railway line between Indija and Novi Sad (Serbia).
Arnold et al.	2004	Optimally locate rail/road intermodal terminals	Linear 0-1 program solved by a heuristic that minimizes total transportation cost for freight transportation.	In the formulation, the terminal is considered as an arc in a graph and not as a vertex.	Iberian Peninsula.
Yamada et al.	2009	Investment planning problem	Lower level solves the multimodal multiclass user equilibrium traffic assignment using a modal split assignment model. Upper level approximately optimizes the selection of actions using GLS, a metaheuristic-based procedure.	Model incorporates traffic and freight flows on the transportation network as the selected actions change traffic conditions, which influence the benefits gained from the actions.	Small transportation network in West Java (Indonesia) and larger transportation network in Philippines.
Maia and Couto	2013	Railway networks planning and policy design	Strategic planning freight traffic assignment model. The optimization process comprises a greedy algorithm, a local search heuristic, and a shaking process.	Considers road and rail. Contemplates intermodal cargo and general cargo, with different assignment process. Includes intermodal terminals and congested rail nodes.	Two fictional networks.
Yamada and Febri	2015	Multimodal freight transportation network development	Two-level discrete optimization model for transportation network within the framework of mathematical programs with equilibrium constraints.	Lower level calculates the quantities and the prices of transported products and the traffic conditions. Upper level selects projects that maximize benefit-cost ratio.	Small and larger-sized hypothetical super networks.
Alireza Seyedvakili et al.	2020	Multiperiod railway network design	Mixed integer model solved by an exact method that minimizes total rail operation cost and total lost demand cost.	Determines the progress rate of each selected project and manages unmet demand in different periods.	Iranian railway network.

Archetti et al. (2022) presented a survey on multimodal freight transportation optimization, considering different combinations of modes. The authors pointed out that environmental aspects, especially carbon emissions, and transshipment cost have been frequently considered in studies and policies over the last few years, and that this trend should be fostered. In addition, there was an increase in multi-commodity problems, in multi-objective studies and in synchro modal transportation problems. On the other hand, congestion at terminals and the effects of the multiple actors' collaboration and competition behaviors in multimodal transportation have been seldom studied, while intermodal studies combining sea transportation and other modes warrant more attention. Another positive finding is that most studies test the proposed methods on real world instances, which compensates the risk of problem overfitting.

3.2. Use of Geographic Information Systems (GIS)

GIS are used in policy making and design and planning processes, as they can solve spatial decision problems, understand spatial patterns, execute complex geographical analysis, and consider environmental factors, such as topography, ecology, and geology (EDLP, 2016a; Hasany and Shafahi, 2017; Mohseni et al., 2016; Rodrigue, 2020; Song et al., 2021). Some relevant studies on railway planning and design that use GIS are presented below, with a special emphasis on freight transportation.

Hasany and Shafahi (2017) proposed a process to find an optimal rail path that is composed of two building blocks: in the first block, a variant of the ant colony optimization (ACO) metaheuristic finds the railway path with the minimum cost between two locations, and in the second block, a GIS database is used to obtain all the necessary data, e.g., elevation data (topography layer), right-of-way cost per square meter, forbidden zones, and geology, to accurately evaluate the total path cost. The total cost is composed of location-dependent cost (right-of-way cost), volume-dependent cost (filling cost, cutting cost, and transportation cost), length-dependent cost (ballast, crosstie, fastening, and signalization costs), traffic-dependent cost (vehicles' acquisition and operating costs and travel time costs), and penalty cost (for not satisfying maximum allowable gradient and minimum allowable radius constraints). The problem is formulated as a continuous optimization problem and the ArcGIS Desktop 9.3x was used to communicate the GIS data to the algorithm. The evaluation of total path cost in GIS software is relatively time consuming, so the procedure creates a narrow corridor around a near optimal solution to minimize the number of GIS uses. It is possible to find a volume-dependent oriented solution, which requires minimum earthwork operations but probably has a longer path, and on the other hand, a length-

dependent oriented solution. The enhanced ant colony system is compared to other five algorithms in eight test functions, with satisfactory results.

Ye et al. (2020) proposed a hybrid integer programming model combining path searching and global integration to solve the metro network layout planning problem. The model is formulated in two phases. Phase 1 is a bi-objective programming model that finds the optimal transit path of each origin–destination (O–D) pair. It is solved by the sequencing method. First, the problem is solved under the objective of minimizing the construction cost of a transit path (station and tunneling cost). Second, an additional budget constraint is added to solve the problem under the objective of maximizing the demand capture intensity of nodes along the path. To reduce the search space, a K-shortest paths (KSP) algorithm is developed to generate the subnetwork for each O–D pair. Phase 2 is a decision model that finds the network layout that maximizes the network transit demand using the outputs of phase 1 and considering transit demands and constraints (total network length, link capacity, graph connectivity, and basic operation characteristics). Data from GIS files are imported to MATLAB to program the basic data acquisition, the O–D pair selection, and the KSP algorithm, and the network matching is done in TransCAD. The proposed model is tested in the city of Xi'an (China) and is compared to the planned network layouts, finding a network with better connectivity and capacity usage.

Song et al. (2021) proposed a two-stage method based on GIS and Analytic Hierarchy Process (AHP) to design a railway alignment. The first stage assesses environmental impact. It generates an elevation accessibility map and analyses the spatial relations of environmental factors (topography, ecology, and geology, divided into 12 sub-factors) with railways using a GIS (ArcGIS). Then, an environmental suitability map is produced that combines these sub-factors with an AHP. In the second stage, an automated railway design is performed. Firstly, the study area is narrowed using the two maps to determine feasible search spaces. After that, a distance transform algorithm integrated with a multi-criteria tournament decision method searches for railway alignments solutions. The method is applied to a real-world case in China and compared to the best manually designed alternative produced by experienced human designers. The starting and ending points of the railway were given. The results showed that the computer-generated railway reduced the construction cost by 7.2% and improved ecologic and geologic performances by 24.4% and 25.0%, respectively, mainly because it reduced the number of long and expensive tunnels and bypassed environmentally sensitive regions. Despite the positive results, the authors note that this method should not replace human designers but can be used to assist the real-world design and decision-making processes.

Jha (2013) presented two metaheuristics, a GA and an ACO, to solve the highway and the railway infrastructure planning and design problems. The problems consist of finding the best economical route (horizontal and vertical alignment), subject to design and operational constraints, e.g., length of vertical curves, gradient, sight-distance, and environment. Apart from the GAs, other search methods are mostly not suitable to the highway problem because of the indirect relationship between the decision variables (points of intersection) and the objective function (total alignment cost). To use the ACO algorithm to solve these problems, it is necessary to discretize the continuous search space. The objective function is the sum of user cost (travel-time cost, vehicle operating cost, and accident cost), right-of-way cost (calculated from a GIS), pavement cost, earthwork cost, and structure cost. The railway design and operational constraints are different from highways, as the geometric curves of the track must safely accommodate the whole train. For urban passenger systems, the station locations are the most important problem, and the objective function is the sum of user, operator, and construction costs. The approximate travel times are obtained from a GIS database. The authors suggest that future studies include objectives of reducing vehicular air pollution, noise level, and fuel cost to achieve environmental and energy sustainability.

Lai and Schonfeld (2016) proposed a methodology that simultaneously optimizes the stations' location and the rail transit alignment between these stations, through a multiple objective model integrated with a GIS database and employing a GA to optimize the decision variables. There is a tradeoff between ridership and cost in the choice of station locations and in the alignment generation between them that is considered in the fitness function. First, the methodology has a procedure to screen the study area and generate a candidate pool of potential rail transit stations based on engineering practice and using GIS to characterize land use. Then, the proposed concurrent optimization model selects the stations' location and the alignment between each pair of adjacent stations that minimizes the total system cost, whilst satisfying station selection and track geometry constraints. The rail track alignment follows the engineering practice with three distinct parts: the choice of stations, which includes station order and station type; the horizontal alignment, defining the track path on the XY plane; and the vertical alignment that specifies the elevation along the path. The total system cost is the total net cost, equal to the difference between initial costs (or capital cost) and the operation and user costs savings, achieved by shifting trips from cars to trains. The GIS database includes the elevation data, used to better estimate the earthwork costs and the structure costs, and the right-of-way cost. The authors combined two types of discrete choice model into the proposed framework to estimate transit ridership forecast: a multinomial logit choice model (for pedestrian-focused facilities) and a nested logit choice model (for Park-and-

Ride stations). Finally, Lai & Schonfeld (2016) tested the proposed concurrent optimization model in the city of Baltimore (USA), demonstrating its advantages over the two-stage optimization model.

Ahmed et al. (2020) developed an integrated multiple-objective optimization model to concurrently optimize multiple rail lines, rail transit station locations and rail lines alignment, using GIS (ArcGIS) and a GA. The model is composed of two stages. The first stage is a GIS-based algorithm that finds feasible station locations based on thresholds of walking distance, number of airport terminals, number of existing rails stations, number of car parking facilities, number of bus stops, area of commercial land use, population density, land value, and proportion of underdeveloped land, and excludes cells that cross environmentally sensitive areas, e.g., historical buildings, national parks, forests, and rivers. The second stage uses a heuristic algorithm based on GA to simultaneously find the subset of feasible station locations and the line network connecting them that best meet the desired objectives of the three stakeholders (passenger, operator, and community costs) and that satisfy the constraints of number of stations in each line, distance between two successive stations, number of transfer stations in each line, and number of common sections between two lines. The passenger cost is the time cost difference between using train and bus or car, the operator cost is the operation and maintenance cost differences between using rail and the other modes, and the community cost is the capital cost necessary to build the stations and the line network that connects them, which needs information from the GIS database. The proposed model was tested in the city of Leicester (United Kingdom). The results showed that finding feasible potential station locations in the first stage directed the search in the second stage into more promising areas, improving the optimization model's performance. In addition, the simultaneous optimization of multiple rail lines generated a solution with a 70% lower total cost and 82% more passengers than the individual lines optimization.

Apivatanagul and Regan (2010) developed a bi-level long-haul freight network design model using shipper-carrier freight flow prediction. A GIS is used to simplify the data management and the analysis of the results. The upper level is a budget allocation model solved by a branch and bound algorithm. The objective function minimizes total social costs (the highway travel time) subject to the budget constraint. The procedure suggests a subset of project improvements to the lower level evaluate and calculate a lower bound, which speeds up the upper level's search process. The lower level symbolizes the user route choice and the shipper-carrier relationship and solves a multiple commodities nonlinear optimization problem. The shipper model allocates freight demand into the network of available services that minimize total costs, while the carrier model routes vehicles based on this transportation services' demand, minimizing travel time, and

obtaining traffic volumes on highway or railway networks. The model is successfully tested in a case study of the state of California (USA) freight transportation network. The upper level's network design model is compared to the ranking method and showed better results. However, the branch and bound procedure cannot efficiently solve more than 16 independent projects, requiring expert knowledge to find a good initial incumbent solution or a heuristic search.

Gallardo et al. (2021) developed a sequential optimization-simulation approach to plan a low carbon freight system considering road and rail modes. The optimization model is a GIS-based freight network design model built in ArcGIS that generates optimal shipping plans (containing origins, destinations, mode allocation and transfer nodes), quantifies traffic through the network, and selects intermodal hubs. The simulation model is a GIS-based discrete event simulation (DES) model implemented on the software Anylogic 8.5.2. The transportation, terminal and production agents interact with each other in a GIS space in response to the shipping plans received from the optimization model. Then the model evaluates the system performance (shipping time, resource utilization, train frequency and queuing time at terminals) under different infrastructure arrangements. The framework was implemented in the North Island (New Zealand). Results showed that, despite the deteriorated railway infrastructure and low train running speed, the rail modal share could be much higher if effective access to the network is provided, especially with the adoption of key intermodal terminals.

Table 9 summarizes the previous studies mentioned in this section.

Table 9. Summary of studies using GIS.

Author(s)	Year	Problem	Method	GIS use	Test case
Hasany and Shafahi	2017	Find the optimal railway path	First block uses a variant of the ACO metaheuristic to find the railway path with the minimum cost; second block applies a GIS database to obtain data to evaluate the total path cost.	Obtain all data to evaluate the total path cost.	An artificial study area.
Ye et al.	2020	Metro network layout planning	Phase 1 is a bi-objective model that finds the optimal path of each O–D pair; phase 2 is a decision model that finds the network layout that maximizes the network transit demand.	Program the basic data acquisition, the O–D pair selection, and the KSP algorithm.	Xi'an (China).
Song et al.	2021	Railway alignment design	First stage assesses environmental impact using GIS and AHP; second stage performs an automated railway alignment design.	Create an environmental suitability map and an elevation accessibility map.	Yichang City, Hubei Province (China).
Jha	2013	Highway and railway infrastructure planning and design	A GA and an ACO metaheuristics to find the best horizontal and vertical alignment.	Calculate right-of-way cost and obtain the travel times for urban passenger systems.	-
Lai and Schonfeld	2016	Rail transit alignment and station locations	Multiple objective model using a GIS database and a GA to simultaneously optimize the stations' location and the rail transit alignment between these stations.	Characterize land use and to better estimate the costs.	Baltimore (USA).
Ahmed et al.	2020	Rail transit system planning	Two-stage integrated multiple-objective optimization model to concurrently optimize multiple rail lines, station locations and rail lines alignment, using GIS and a GA.	GIS-based algorithm that finds feasible station locations and calculate construction cost.	Leicester (United Kingdom).
Apivatanagul and Regan	2010	Long-haul freight network design	Upper level is a budget allocation model solved by a branch and bound algorithm. Lower level solves a multiple commodities nonlinear optimization problem.	Data management and analysis of the results.	California (USA) transportation freight network.
Gallardo et al.	2021	Multimodal freight transportation planning	Sequential optimization-simulation approach considering road and rail modes.	GIS-based freight network design optimization model and a GIS-based DES model.	North Island (New Zealand).

3.3. Freight transportation planning and design and GIS in Brazil

Isler et al. (2021) located new railway terminals in the existing freight transportation network of the state of Santa Catarina (Brazil). A GIS tool was used to propose an initial set of links connecting the geographic center (nodes) of Santa Catarina's microregions by means of a Delaunay triangulation, thus generating connections without intersections between links out of the nodes. It resulted in a railway network composed of existing and candidate rail links. Then, given the volume of 35 products grouped into four classes (bulk, containerized, refrigerated, and liquid cargo), an all-or-nothing assignment procedure was applied to the network, resulting in freight flows estimations for each link. The total freight volume assigned per link was transformed into the number of daily trains, and the links with at least six daily trains were selected as the new links to be connected to the future transportation network. Next, a set of intermodal terminals is selected based on an analysis of the new and existing road and railway infrastructure and finally classified as Feeder, Small Terminal, or Container Hub-Feeder Service depending on its region, types of products operated, the number of railway links and their total volume. The GIS software was also used to visualize the collected datasets, to illustrate different scenarios, and to match them with the geographical features of Santa Catarina.

Plaza et al. (2020) presented a capacitated multi-layer location-allocation mathematical model to determine the optimal location of logistics integration centers (LICs) for the Brazilian soybean transportation, considering transportation and installation costs and CO₂ emissions. Firstly, 80 candidate microregions were chosen to receive an LIC due to having transshipment and multimodal terminals and being close to the production zones and far from the environmental protection areas. Then, several scenarios were built to evaluate the economic and environmental impact of opening LICs. The results showed the importance of LICs and of multimodality in reducing transportation costs and CO₂ emissions and in increasing the efficiency of the logistics systems operation.

De La Cruz et al. (2010) developed a nonlinear spatial temporal multimodal transshipment equilibrium model to choose the best infrastructure investment for the state of Tocantins' soybean exporting routes. The objective is to maximize the Net Social Payoff Function (NSP), which is the sum of excess demand and excess supply, minus the transportation, warehousing, and transshipment costs. Two periods were considered: harvest and non-harvest season. Four scenarios were analyzed, and the best result was achieved with the Tocantins-Araguaia waterway (located in the E2-E5, F2-F4 grids of Annex B – "Brazil's 2035 expected cabotage routes, waterway network, ports, and terminals").

Silva-Neto (2018) proposed a linear transportation program that minimizes the road, rail, and water transportation costs and the port elevation and multimodal transshipment costs to evaluate the economic impact of infrastructure projects in the Brazilian soybean and maize logistic chains, with focus in export markets. The largest reduction in logistic costs was achieved by doubling the exporting capacity of the Arco Norte, followed by the implementation of Ferrogrão railway (located in the D3-D4 grids of Annex A) and duplication and paving of the BR-163 road up to Miritituba/Itaituba (state of Pará - PA, located in the D3 grid of Annex A). The Ferrogrão runs parallel to the BR-163 road.

Branco et al. (2020) proposed a two-step procedure to evaluate the economic and environmental impacts generated by the addition of five new railways (North-South Railway (FNS), West-East Integration Railway (FIOL), Rumo Malha Norte, New Northeastern Railway (NTN), and Ferrogrão) to the Brazilian transportation network. In the first step, the interregional transportation flows of Brazilian soybean and maize are simulated in a network equilibrium model that minimizes total freight cost, while the benefits measured are reduction in transportation costs and CO₂ emissions. The model considered 558 origins, 67 transshipment terminals, 14 exporting terminals, and 149 consumption regions. GIS (TransCAD software) was used to calculate the Origin-Destination (O-D) distance matrix. In the second step, a cost-effective analysis is used to rank the new railways. Ferrogrão presented the highest return on investments, followed by Rumo Malha Norte between Rondonópolis (state of Mato Grosso - MT, located in the D6 grid of Annex A) and Cuiabá (MT, located in the D5 grid of Annex A) and FNS between Palmas (state of Tocantins - TO, located in the F4 grid of Annex A) and Estrela D'Oeste (state of São Paulo - SP, located in the E6 grid of Annex A)). On the other hand, FIOL (located in the F5-G5 grids of Annex A) and NTN (located in the F3-F4, G3-G4 grids of Annex A) have lower returns and may require partial public funding to attract private investments.

Rocha (2020) analyzed the efficiency of 26 multimodal infrastructure projects to the Brazilian soybean's transportation considering economic, environmental, and social impacts. Firstly, each project has its impacts simulated on a network equilibrium model for minimizing transportation costs. In the baseline model, which contains only the existing infrastructure, the multimodal transported volume was approximately 80% of the actual numbers. This difference is justified by the different commercial strategies adopted, the high number of agents transacting in the Brazilian soybean market, and the origins aggregated by municipality. Afterwards, a set of indicators, including the potential cost reduction, CO₂ emissions, physical losses in transportation operations, and area of influence of the new infrastructure, were used to evaluate the relative efficiency of the selected projects in a Data Envelopment Analysis (DEA) model. The result

showed that the most efficient project is a waterway stretch from Marabá (PA, located in the E3 grid of Annex A) to the port of Barcarena (PA, located in the F2 grid of Annex A), followed by the joint stretches of the FNS (located in the F4, E5-E6 grids of Annex A) and of FICO (located in the E5 grid of Annex A) and the expansion of Rumo Malha Norte railway until Sinop (MT, located in the D4 grid of Annex A).

João (2021) developed a network equilibrium model using Linear Programming (LP) and Mixed Integer Programming (MIP) to evaluate the infrastructure improvements that optimize soybean and maize logistics in Brazil. The objective function is the total logistics cost, comprising multimodal transportation, storage, and port costs. The mathematical model considers storage and monthly periods, allowing a seasonality assessment across the year. The infrastructure improvements considered are increase in the capacity of ports, factories, transshipment terminals, and static storage. The distance between O-D points was calculated using GIS (Maptitude software). Results showed that the transshipment terminal of port of Miritituba (PA, located in the D3 grid of Annex A) has a large area of influence, attracting cargo from Rondonópolis terminal (MT, located in the D6 grid of Annex A) when increasing its capacity.

Péra (2022) developed a multi-objective multi-period network transportation optimization model to generate Pareto Frontiers and evaluate the impacts of technological and infrastructural changes on the promotion of Brazilian soybean green logistics in the long term. The objective functions considered are costs, CO₂ emissions, losses in logistics activities, diesel oil and maritime heavy fuel oil demand, truck demand, and intensity of transportation modes (road, rail, waterway, and maritime). GIS (TransCAD software) was used to calculate the distance between O-D points. Firstly, the elasticities of the model parameters (such as transportation productivity, energy efficiency, infrastructure capacity, and ship capacity) were estimated. Then, the model results showed that there is a trade-off between logistical costs and CO₂ emissions considering the same level of technology and infrastructure, but improvements caused the Pareto Frontiers to shift towards win-win solutions, with reduction of both costs and emissions. The best results were obtained with the reduction of truck loading and unloading times, the increase in energy efficiency of trucks and trains, the expansion of existing rail and barge infrastructure, the inclusion of new railroads, and the replacement of Panamax ships by Capesize ships.

The abovementioned studies are summarized in Table 10. Except for Plaza et al. (2020) and Isler et al. (2021), all other studies evaluate several multimodal projects in different scenarios, searching for the best performance according to the selected objective function.

Table 10. Summary of studies on freight transportation planning and design and using GIS in Brazil.

Author(s)	Year	Problem	Method	Characteristics	GIS use
Isler et al.	2021	Railway terminals' location	All-or-nothing assignment procedure generates freight flows estimations for each link. Next, intermodal terminals are selected based on the new and existing road and railway infrastructure.	Focus on the state of Santa Catarina.	Propose an initial set of links connecting the nodes by means of a Delaunay triangulation, visualize the collected datasets, and illustrate different scenarios.
Plaza et al.	2020	Logistics integration centers' location	Capacitated multi-layer location-allocation mathematical model.	Minimizes logistics and environmental costs. Focus on soybean transportation.	-
De La Cruz et al.	2010	Multimodal infrastructure projects' evaluation	Nonlinear spatial temporal multimodal transshipment equilibrium model.	Maximizes the Net Social Payoff Function. Focus on the state of Tocantins' soybean exporting routes.	-
Silva-Neto	2018	Multimodal infrastructure projects' evaluation	Linear transportation program.	Minimizes multimodal costs. Focus on soybean and maize logistic chains, especially export markets.	-
Branco et al.	2020	Railway projects' evaluation	First step is a network equilibrium model that minimizes total freight cost. Second step is a cost-effective analysis that ranks the new railways.	The benefits measured are reduction in transportation costs and CO ₂ emissions. Focus on interregional transportation flows of soybean and maize.	Calculate the O-D distance matrix.
Rocha	2020	Multimodal infrastructure projects' efficiency analysis	First, projects' impacts are simulated on a network equilibrium model that minimizes transportation costs. Then, the projects' relative efficiency is evaluated in a DEA model.	Considers economic, environmental, and social impacts. Focus on soybean transportation.	-

Author(s)	Year	Problem	Method	Characteristics	GIS use
João	2021	Multimodal infrastructure improvement projects' evaluation	Network equilibrium model using Linear Programming (LP) and Mixed Integer Programming (MIP).	Considers storage and monthly periods. Minimizes total logistics cost. Focus on soybean and maize logistic chains.	Calculate the O-D distance.
Péra	2022	Technological and infrastructure improvements' evaluation	Multi-objective multi-period network transportation optimization model to generate Pareto Frontiers.	Objective functions are costs, CO ₂ emissions, losses in logistics activities, fuel and truck demand, and intensity of transportation modes. Estimation of the model's parameters elasticities. Focus on soybean green logistics.	Calculate the O-D distance.

In the real world, railway design in Brazil has evolved. For instance, the first Center-West Integration Railway (FICO) project in 2008 considered the origin in Uruaçu (state of Goiás - GO, located in the F5 grid of Annex A) and the destination in Vilhena (state of Rondônia - RO, located in the C5 grid of Annex A). In 2010, the revised basic project considered the origin in Campinorte (GO, located in the F5 grid of Annex A). In 2014, the technical, economic, and environmental feasibility studies were audited, and several shortcomings were found, such as engineering studies with insufficient degree of precision, inaccuracy in the values of the properties to be expropriated, duplicity of railway equipment, and need for improvements in the demand study. After further required revisions, the final path was defined in 2018 between Mara Rosa (GO, located in the E5 grid of Annex A) and Vilhena (RO), with improvement in the ramp efficiency and increase in the curve radius, optimizing traffic conditions and the operation efficiency (Agência INFRA, 2018; Mararosa.com, 2019; Tagliari, 2018; TCU, 2014).

On the other hand, the Ferrogrão railway was designed following a framework of determining the demand, then the best operational setup, and finally the best infrastructure. Before the Brazilian government decided to invest in the development of the Ferrogrão's technical studies, a demand study was conducted to evaluate the best economical possibility to transport the Center-West grains to the exporting ports. To determine the origin and destination points, some options were selected by the designers based on their expertise (such as Lucas do Rio Verde (MT, located in the D5 grid of Annex A) and Sinop (MT, located in the D4 grid of Annex A)) and were evaluated on a simulator. The best economical results were obtained by a railway between Sinop and Itaituba (PA, located in the D3 grid of Annex A), later called the Ferrogrão. The demand was calculated by municipality in the state of Mato Grosso and by mesoregion in the other states. The future production volume was estimated based on growth expectations of the productive area (low, medium, and high growth), considering just official productive areas, and excluding environmental protected areas. Only publicly available data were used (EDLP, 2022).

After the starting and ending points of the railway were chosen, the preliminary engineering studies were executed. These studies' objective was to create a conceptual project, evaluating the project feasibility, main costs, main socio-environmental impacts, and demand coverage in a small-scale map. As the considered area is largely limited by environmental protected areas and by the BR-163 highway, there were few path possibilities, and they were determined by the designers through the testing of variables and following the government guidelines, such as the use of AHP. The main criterion considered in the AHP was the environmental impact. The four path alternatives were very similar (the railway was divided into two sectors, and two similar alternatives for each sector were proposed) (EDLP, 2022, 2016a).

The intermediary terminal in Matupá (MT, located in the D4 grid of Annex A) was determined in the following studies. The analysis of the results showed that the railway was not capturing all the potential demand of the North of Mato Grosso, because it would require a negative trip to Sinop. Thus, using the designers' expertise, some potential terminal locations were tested, and the best result was achieved with an intermediary terminal in Matupá (EDLP, 2022).

The detail level increased from the preliminary (small-scale map) to the initial and the definitive engineering studies (large-scale map), in a feedback process: a more detailed demand study changed the operational setup study, which in turn caused adjustments in the infrastructure study, and so on. In the demand study, the selection of products was done based on the states' production and consumption data, while the definition of the area of influence was through a demand capture gravitational model; both were combined with the designers' expertise (EDLP, 2022).

4. METHOD

This chapter details the case study used in this thesis to illustrate the proposed model and defines the two-level optimization model, including the mathematical models, the solution method, and the used parameters and multimodal transportation network. Section 4.1 presents the current scenario for maize, soybean, and soybean meal in Brazil and justify their selection as the case study. Section 4.2 shows the first level model, while section 4.3 presents the second level model.

To improve the Brazilian logistics network for the domestic market of agricultural products in a more sustainable way, this thesis proposes a two-level optimization model for transportation and warehouse networks integrated with a GIS, inspired by Yamada et al. (2009), Isler et al. (2021), Maia and Couto (2013), Gallardo Ocampo (2020), Gallardo et al. (2021), Archetti et al. (2022), João (2021), and ESALQ-LOG (2020).

In the first level (section 4.2), a railway network design model is solved by a constructive heuristic to find a new railway connecting the Center-West and South regions that maximizes the benefit-cost ratio. In the second level (section 4.3), a linear programming problem is developed to optimize the Brazilian agricultural products logistic network, calculating the O-D flows and storage volumes that minimize the total logistic cost and the CO₂ emissions.

Hence, the proposed model designs a new railway to link the Center-West and the South regions; selects the location of warehouses that need to increase the static capacity and determine the necessary volume; assess the most used transportation infrastructures; and find the most promising entry points to import maize from Paraguay, Argentina, and other countries.

4.1. Case study: maize, soybean, and soybean meal

The proposed method will be applied to the maize, soybean, and soybean meal simplified supply chains. The selected products were chosen because they are among the most transported products in Brazil in 2017¹², according to PNL-2035 data survey: soybean (fifth place, 272 million tonnes or 7%), maize (sixth place, 173 million tonnes or 5%), and soybean meal (tenth place, 135 million tonnes or 4%) (EPL, 2021a). This transported volume includes intermediate flows; thus, it is higher than the production volume.

Maize and soybean were responsible for the production and movements of more than 219 million tonnes in 2019. Their transportation to export markets changed since 2010, with the

¹² This section presents data from several sources; so, the year of the data varies with the source.

expansion and consolidation of new transportation corridors, the use of new railways and waterways, the expansion of the agricultural frontier, and the need to alleviate traffic congestion on traditional exporting corridors. The long distances between the major producing regions and the rail and barge terminals (average distance of 707 kilometers) and its limited infrastructure capacity are challenges that persist, so that road mode is still relevant (Péra et al., 2021).

On the other hand, transportation to domestic markets is done almost exclusively by road, with an average distance of 574 km, and this dominance has not changed since 2010: 99% in 2010 and 98% in 2019 for maize, and 97% in 2010 and in 2019 for soybean. This modal split of freight transportation does not consider short-haul trucks (pre-haul) in order to avoid double counting. In 2019, the volume transported to the domestic markets was of 55.8 million tonnes for maize and 44.3 million tonnes for soybean (Péra et al., 2021).

Maize's volume destined to export markets increased significantly between 2010 and 2019, from 11 million tonnes (19% of production) to 43 million tonnes (43% of production). Its transportation matrix is dominated by railway, although its participation reduced from 78% in 2010 to 50% in 2019, while road and barge increased their shares from 20% to 31%, and from 3% to 20%, respectively. The average railways distance for the 2010-19 period was of 1,260 km and the average barge distance was of 1,075 km (Péra et al., 2021).

Soybean presented the same trend as maize. Its volume destined to export markets increased significantly between 2010 and 2019, from 29 million tonnes (42% of production) to 74 million tonnes (62% of production). Its transportation matrix is dominated by the road mode, which increased its participation from 45% in 2010 to 49% in 2019, while railways' share reduced from 47% in 2010 to 38% in 2019, and barge increased its share from 8% to 13%, respectively. The average railways distance for the 2010-19 period was of 1,050 km and the average barge distance was of 990 km (Péra et al., 2021).

Although maize and soybean's volume transported in railways and waterways increased significantly from 2010 to 2019 (27.6 million tonnes and 15.1 million tonnes, respectively), the new infrastructure did not have enough capacity to transport the increasing exported volume, such that the volume increase in the road mode was much higher (34.3 million tonnes) (Péra et al., 2021).

Regarding the domestic market, maize and soybean meal's main consumer is the animal feed industry and especially the poultry and pork sectors. Soybean's main destination in the domestic market is the crushing plant, that produces soybean meal and soybean oil (Safras&Mercado, 2022a).

The three states located in the Southern region of Brazil (Santa Catarina, Rio Grande do Sul, and Paraná), are the top three producers of chicken and pig meat in Brazil. Paraná is the largest

chicken meat producer in the country (36% of total production), followed by Santa Catarina (15%), and Rio Grande do Sul (14%); while Santa Catarina is the main pig meat producer (32% of total production), with Rio Grande do Sul in the second place (21%), and Paraná in the third place (19%) (ABPA, 2022).

The poultry and pork sectors are of high socioeconomic importance and are among the main production chains in the states of Santa Catarina and Rio Grande do Sul. In addition, they are part of their culture and tradition since the late 19th and early 20th centuries and contribute to food security in Brazil and in other countries. The poultry and pork sectors of these states have several competitive advantages, such as high level of productivity and animal health security (being recognized by the World Organization for Animal Health (OIE) as a free zone of foot and mouth disease (FMD) without vaccination); integrated production organized in cooperatives and associations; local communities with qualified and specialized workers; and proximity to important exporting ports, such as Itajaí (SC, located in the F8 grid of Annex A), São Francisco do Sul (SC, located in the F8 grid of Annex A), and Rio Grande (RS, located in the E9 grid of Annex A) (ABCS, 2016; BRDE, 2017; Epagri/Cepa, 2021; ESALQ-LOG, 2020; MAPA, 2021).

The main inputs for poultry and pig feed are maize and soybean meal. A chicken with 2.8 kg live weight needs 3.44 kg of maize (63% of the average feed), 1.64 kg of soybean meal (30%), and 0.19 kg of soybean oil (3.5%). A swine with 118 kg of live weight requires 235 kg of maize (71% of the average feed) and 66 kg of soybean meal (20%) (Santos-Filho et al., 2018). In the past few years, maize production in these states has decreased, mainly due to farmers increasing the soybean planted area, as it provides higher economic returns. On the other hand, chicken and pig meat production has increased (although in a slower rate than other Brazilian states), resulting in an annual maize deficit of around 4.4 million tonnes for Santa Catarina and 1.5 million tonnes for Rio Grande do Sul (BRDE, 2017; DPADR, 2019; Epagri/Cepa, 2021; ESALQ-LOG, 2020). Regarding soybean meal, Santa Catarina's deficit is much smaller: around 1.5 million tonnes, while Rio Grande do Sul is self-sufficient (ESALQ-LOG, 2020).

Although the states of Santa Catarina and Rio Grande do Sul have significant competitive advantages in the poultry and pork production, this scenario of longstanding deficit of its main input has increased production costs and has led large poultry and pork industries to reduce investments and close facilities in these states and to establish new production plants in the Center-West region of the country, where maize is abundant. It is estimated that this shift generates a 30% reduction in production costs for the poultry industry, mainly due to lower cost of maize, to reduction in logistical costs, and to better use of perishable products. Santa Catarina also faces other bottlenecks such as the lack of infrastructure and environmental problems due to waste

(ABCS, 2016; Aquino, 2016; Ascoli and Orłowski, 2008; ESALQ-LOG, 2020).

The main producers of maize in 2020 were the states of Mato Grosso (MT), Paraná (PR), Goiás (GO), Mato Grosso do Sul (MS), Minas Gerais (MG), São Paulo (SP), Rio Grande do Sul (RS), and Santa Catarina (SC), in descending order (IBGE, 2022b). Paraná is the closest state to Santa Catarina and Rio Grande do Sul, but its own poultry and pork industries and most recently ethanol production consume most of the state's maize production, leaving a surplus of around 1.3 million tonnes. Thus, Santa Catarina and Rio Grande do Sul must procure maize from further states with higher surplus (Mato Grosso do Sul and Mato Grosso, both located in the Center-West region) or even other countries (Paraguay and Argentina) (Epagri/Cepa, 2021; ESALQ-LOG, 2020; MAPA, 2022; Safras&Mercado, 2022a). As the maize-based ethanol, poultry, and pork sectors of the Center-West states keep expanding and the international demand remains high, these states' surplus are decreasing and the maize price is increasing (ESALQ-LOG, 2020).

The geographical localization of the Brazilian states is displayed in Figure 10.

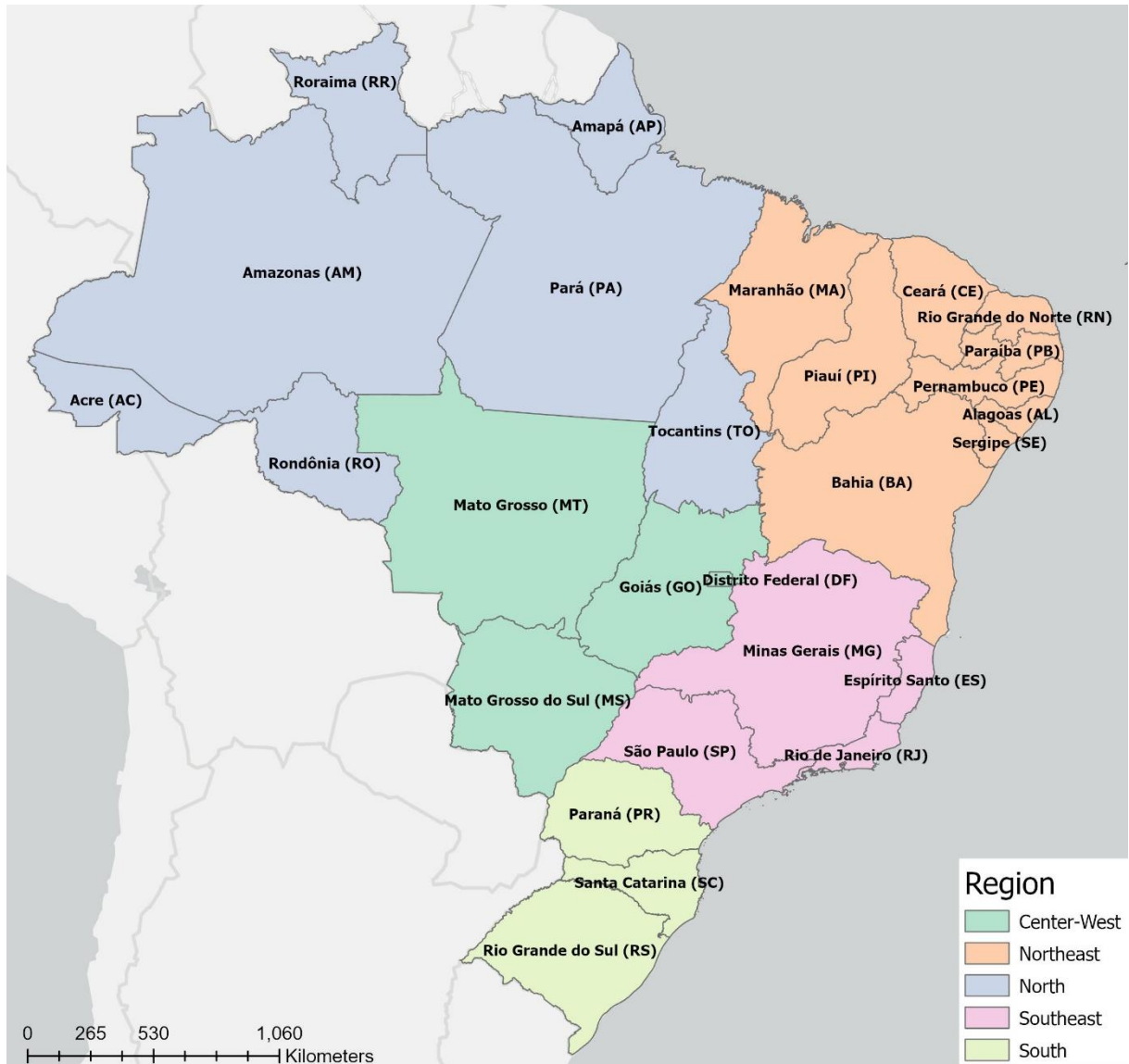


Figure 10. States and regions of Brazil.

Source: IBGE (2022a).

Another hindrance for the maize supply is the seasonality. Poultry and pork production volume (and consequently their inputs demand) have low variability throughout the months, but Santa Catarina's and Rio Grande do Sul's maize production is harvested mainly between February and April (first-crop), while the Center-West main volume is harvested between July and September (second-crop) (CONAB, 2022a; ESALQ-LOG, 2020; IBGE, 2022c, 2022b). Thus, from February to April, the sector acquires the local maize production to meet its feed demand. From May to July, the sector consumes the local maize stored after the harvest, completing the required volume with purchases mainly from Paraná and Mato Grosso do Sul, as well as from Paraguay and Argentina. Between August and October, maize harvested in the states of Mato Grosso do Sul, Paraná, and Mato Grosso and in South American countries is acquired and stored. Finally, between November

and January, the maize stored in the previous period is used, and the necessary volume is complemented with the remaining production from Mato Grosso do Sul, Paraná, and Mato Grosso and from other countries (ESALQ-LOG, 2020).

The period with the highest need for maize from other states (between August and January) corresponds to the period of higher freight values and lower truck availability, due to the great transportation demand generated by the Center-West second-crop harvest period (ESALQ-LOG, 2022, 2020). The Center-West local infrastructure (especially in Mato Grosso) was built focused on product transportation to exporting ports; hence, it is more efficient to move maize to exporting ports rather than to Brazil's Southern livestock sector (USDA, 2022). As aforementioned, domestic transportation of maize is carried out by trucks with capacity of 37 tonnes. Thus, Santa Catarina requires more than 115,000 trucks trips to settle its maize deficit of around 4.4 million tonnes, while Rio Grande do Sul needs more than 40,000 truck trips (deficit of circa 1.5 million tonnes). The increase in the distance traveled (for instance, the distance from Maracaju (MS, located in the D7 grid of Annex A) to Chapecó (SC, located in the E8 grid of Annex A) is 830 km and to Arroio do Meio (RS, located in the E8 grid of Annex A) is 1,170 km; the distance from Cascavel (PR, located in the E7 grid of Annex A) to Chapecó is 340 km and to Arroio do Meio is 680 km), the difficulty to hire truck transportation, and the freight cost increase (especially during the Center-West harvest season), sometimes more than offsets the lower maize prices.

This period of higher freight values and lower truck availability could be avoided using a storage strategy, which would also increase stability and guarantee supply. In general, stock levels are lower during the sowing period, leading to an increase in the maize price, while it tends to decrease during the harvest period, when the supply is high. Direct transmission of prices between regions and states of Brazil, or between countries, does not always occur (Alves et al., 2018; ESALQ-LOG, 2020). Thus, the poultry and pork sectors from the states of Santa Catarina and Rio Grande do Sul could buy and eventually store maize when the total cost (sum of maize price, freight cost, and storage cost) is lower. However, the static storage capacity of these states is not high enough to always benefit from this strategy (ESALQ-LOG, 2020).

In Santa Catarina, there were public policies to encourage the construction of warehouses, especially by cooperatives, resulting in a significative increase in the static storage capacity since 2008. Currently, the state has a static storage capacity of 6.3 million tonnes, with 5.5 million tonnes of the bulk type and 0.8 million tonnes of the conventional type. Among the poultry and pork producing microregions, Joaçaba (located in the E8 grid of Annex A), Concórdia (located in the E8 grid of Annex A), and São Miguel do Oeste (located in the E8 grid of Annex A) have high

deficits and could greatly benefit from investments in storage (CIDASC, 2013; CONAB, 2022b; ESALQ-LOG, 2020; OCESC, 2021).

The static storage capacity of Rio Grande do Sul is much higher than that of Santa Catarina, with 32.2 million tonnes distributed between bulk (30.0 million tonnes) and conventional (2.3 million tonnes), but it is concentrated around the area of the port of Rio Grande (located in the E9 grid of Annex A). The remaining volume is not sufficient to store the production of soybean, rice, wheat, and maize. In addition, the state has a deficit in the drying capacity, which is an operation that reduces the moisture content of grains and is performed in the warehouse prior to storage (CONAB, 2022b; DPADR, 2019; ESALQ-LOG, 2020). Maize produced in the Missões region (located in the E8 grid of Annex A) has an average of 26% to 28% moisture content, while in the rest of the state the average is 20% to 22%. To avoid the proliferation of mycotoxins and problems with fungi (that compromise maize use as animal feed) and to increase its shelf life, it is recommended that maize must have a maximum moisture content of 14%. Thus, local production must necessarily go through the drying process in a warehouse. Higher moisture contents demand longer drying times, higher required capacity, and higher costs to reach the ideal moisture rate (ESALQ-LOG, 2020).

Both the government and the private sector of the states of Santa Catarina and Rio Grande do Sul have sought several alternatives to minimize the maize supply bottleneck. In the short-medium term, the main actions include increase the static and the drying capacity of the warehouses; improve the road infrastructure of the main routes used to supply the local feed mills; increase the local maize productivity; and improve the logistic network to import maize from other South American countries. In the long term, it is recommended the construction of new railway networks that could reduce the maize transportation costs from the Center-West region, and the research of cultivars of other cereals (such as wheat and barley) that could effectively replace or complement maize in animal feed. Rio Grande do Sul has a smaller deficit, then an increase in maize production combined with an increase in storage capacity may significantly reduce the maize deficit. On the other hand, Santa Catarina is a small state and has a larger deficit, so even with all the interventions to stimulate an increase in local production, it will still heavily depend on maize bought from other states (ESALQ-LOG, 2020).

Thus, maize, soybean, and soybean meal's transportation should benefit from a new railway connecting the Center-West and South regions, as well as from an increase in the static storage capacity of bulk warehouses in these regions. Their socioeconomic relevance to Brazil justifies their selection as the case study applied in this thesis.

4.2. Railway network design model

The first level of the proposed method is a railway network design model. Its objective is to find the links and terminals of a new railway that maximizes the benefit-cost ratio. The benefit is measured as the reduction in total transportation cost due to the use of the new railway, while the cost is the total railway construction cost. Thus, a greater volume transported by the new railway means a greater benefit (numerator); however, a longer new railway leads to higher costs (denominator).

The model is integrated to the GIS software ArcGIS Pro 3.0 to find the most economical road or multimodal route in the Brazilian multimodal transportation network (ESRI, 2023). As this is a time-consuming task, a constructive heuristic combined with local search is developed to solve this problem.

The ArcGIS Pro software was selected since it is widely used in academical papers (Ahmed et al., 2020; Gallardo et al., 2021; Hasany and Shafahi, 2017; Kotikov, 2015; Mohseni et al., 2016; Song et al., 2021; Suárez-Vega et al., 2011) and in the real world (EDLP, 2016a), and has an affordable version for student use.

The problem can be summarized as: consider a cargo matrix with O-D pairs. The v_{ij} volume from each origin i ($i = 1, \dots, n$) can reach each destination j ($j = 1, \dots, o$) through the Brazilian transportation network using two combination of modes ($k \in \{1 = \text{road}, 2 = \text{multimodal}\}$) and considering the allocation percentage p_{ijk} , that depends on the difference between the modes' transportation costs f_{ijk} . A new railway can be constructed with a unitary construction cost of b per kilometer (for the links) and t per terminal. The railway network design model consists of selecting the railway links x_l ($l = 1, \dots, p$) and the railway terminals y_m ($m = 1, \dots, q$) that will be built such that all volume is allocated and the benefit-cost ratio is maximized.

The mathematical model is as follows:

$$\max_{x,y} Z = \frac{FC_0 - FC}{CC} = \frac{\sum_{i=1}^n \sum_{j=1}^o \sum_{k=1}^2 p_{ijk}^0 f_{ijk}^0 v_{ij} - \sum_{i=1}^n \sum_{j=1}^o \sum_{k=1}^2 p_{ijk} f_{ijk} v_{ij}}{b \sum_{l=1}^p e_l x_l + t \sum_{m=1}^q y_m} \quad (1)$$

subject to

$$p_{ij1} = \begin{cases} 10\%, \text{ if } 1 - \frac{f_{ij2}}{f_{ij1}} > 20\% \\ 20\%, \text{ if } 1 - \frac{f_{ij2}}{f_{ij1}} > 10\% \text{ and } \leq 20\% \\ 30\%, \text{ if } 1 - \frac{f_{ij2}}{f_{ij1}} > 1\% \text{ and } \leq 10\% \\ 90\%, \text{ if } 1 - \frac{f_{ij2}}{f_{ij1}} > 0 \text{ and } \leq 1\% \\ 100\%, \text{ if } f_{ij2} = f_{ij1} \end{cases} \quad i = 1, \dots, n; j = 1, \dots, o \quad (2)$$

$$\sum_{k=1}^2 p_{ijk} = 1 \quad i = 1, \dots, n; j = 1, \dots, o \quad (3)$$

where,

FC_0 = total transportation cost, using the existent transportation network (in R\$);

FC = total transportation cost, using the existent transportation network plus the new railway (in R\$);

CC = new railway's total construction cost (in R\$);

v_{ij} = volume to be transported from origin i to destination j (in tonnes of cargo);

f_{ijk} = transportation cost from origin i to destination j using mode k ($k \in \{1 = \text{road}, 2 = \text{multimodal}\}$) (in R\$/tonne of cargo);

p_{ijk} = percentage of volume transported from origin i to destination j using mode k ;

b = railway link construction cost (in R\$/km);

$$x_l = \begin{cases} 0, \text{ if railway link } l \text{ is not built} \\ 1, \text{ if railway link } l \text{ is built} \end{cases} \quad l = 1, \dots, p;$$

e_l = extension of railway link l (in km);

t = railway terminal building cost (in R\$);

$$y_m = \begin{cases} 0, \text{ if railway terminal } m \text{ is not built} \\ 1, \text{ if railway terminal } m \text{ is built} \end{cases} \quad m = 1, \dots, q.$$

The objective function in Equation (1) maximizes the benefit-cost ratio. The constraint in Equation (2) is the deterministic rule used to allocate flow between road and multimodal routes. The constraint in Equation (3) ensures that all volume is allocated between the transportation modes.

To illustrate the application of the proposed model, a railway to link the Brazilian Center-West and South regions is created. These regions were selected since there are currently no railways

that directly link their domestic markets. On the other hand, there are some railways' projects under development, such as FNS and Nova Ferroeste, that will be used to evaluate the model's performance.

The states of Mato Grosso, Mato Grosso do Sul, Goiás, and Paraná were selected because they are the main maize producers and have the highest surpluses in the country, while Santa Catarina and Rio Grande do Sul are two of the largest maize importers in Brazil (Safras&Mercado, 2022a). In addition, the new railway must pass through these states to connect the Center-West and the South regions.

Among the traffic assignment procedures, the all-or-nothing technique is the simplest and is recommended when other techniques demand a complex implementation or are not suitable to the adopted approach. However, it does not reflect the real world, since the transportation flow between two nodes is spread through several alternative routes mainly due to capacity constraints and different cost perceptions by the users (Jourquin, 2006; Maia and Couto, 2013).

The stochastic-multiflow technique distributes traffic among the different possible routes and transportation modes, so that the path with the least generalized costs receives most, but not all traffic. This is an interesting feature for strategic aggregated models that uses estimates of the average costs as generalized transportation costs and that are not able to incorporate factors which influence the modal or route choice, such as shipment size, frequency of service, service quality, and integrated door-to-door logistic chain. The stochastic-multiflow technique uses the logit formulation to distribute traffic due to its versatility and convenience and it shows the percentage of traffic using each mode (Maia and Couto, 2013). The percentage of trips (P_{ij}^k) from an origin i to a destination j using route k , chosen among a set of n alternative options, is given by the following equation in the multinomial logit model (Tsamboulas and Moraitis, 2007):

$$P_{ij}^k = \frac{e^{-\beta \cdot C_{ij}^k}}{\sum_{k=1}^n e^{-\beta \cdot C_{ij}^k}} \quad (4)$$

where C_{ij} is the generalized cost of travel from i to j through route k and $-\beta \cdot C_{ij}^k$ is the utility function of route k for the O-D pair $i - j$ (Tsamboulas and Moraitis, 2007). There is no generally accepted value for the parameter β , so it must be estimated using collected data, revealed preference studies, or calibrated to represent the observed dispersion of choices. Ultimately, the flow could be divided among the different alternative routes by their relative weights and the assignment becomes purely deterministic. Whichever the case, the assignment results are different from the results obtained using an all-or-nothing or an equilibrium method (Jourquin, 2006).

This thesis is going to minimize total transportation costs instead of the total generalized costs because of the availability of information. In addition, due to implementation complexity, a deterministic rule is used to assign the traffic flow.

Furthermore, this thesis uses the O-D cargo matrix from the PNL-2035, that will be detailed in section 4.2.2. There are 2,573,701 O-D pairs in 2017 and 2,571,162 O-D pairs in 2035 (EPL, 2021d). As the number of O-D pairs is very large, only two routes will be considered for each O-D pair: the most economical road route and the most economical multimodal route. These routes are obtained using the Route tool from ArcGIS Pro (ESRI, 2023).

In addition, the set of links of the potential new railway is built using the Delaunay triangulation algorithm (Isler et al., 2021), connecting a set of nodes in the states of Mato Grosso, Mato Grosso do Sul, Goiás, Paraná, Santa Catarina, and Rio Grande do Sul.

The Delaunay triangulation for a given point set P is a particular triangulation built on the points in P that satisfies the empty circum-circle property, in which the circum-circle of each triangle does not contain any point of the set $p \in P$. Hence, this algorithm connects the nodes without intersection between the links (Cignoni et al., 1998; Isler et al., 2021). The links (edges) were created in ArcGIS Pro using the tools “Create TIN” and “TIN Edge” (ESRI, 2023).

The sides of the polygons created by Delaunay triangulation represent the railway links connecting the set of points (nodes) that denotes the potential railway terminals (Isler et al., 2021). Since the proximity to producing or consumption areas is the main reason for using a terminal and a railway, and it is not feasible to open a terminal in every municipality, the set of potential railway terminals (points) is virtually located in the geographic center of four options: immediate geographic region’s¹³ municipality with the highest flow volume, immediate geographic region weighted mean center by total flow volume, microregion’s municipality with the highest flow volume, and microregion weighted mean center by total flow volume. The test results determine which option of geographic center generates a railway with the best performance. The geographic center was calculated in ArcGIS Pro using the tool “Mean Center” (ESRI, 2023).

Another heuristic’s parameter to be defined through tests is the area of influence and potential cargo. Seven options are considered: Brazilian O-D cargo matrix total volume, Center-West and South regions and its neighboring states cargo matrix total volume and only agricultural bulk solids, Center-West and South regions and its neighboring intermediate geographic regions or mesoregions cargo matrix total volume and only agricultural bulk solids, and Center-West and

¹³ The immediate and intermediary geographic regions were created in 2017, as an update of the microregion and mesoregion classifications due to the economic, demographic, political and environmental changes that occurred in Brazil over the last few decades (IBGE, 2018).

South regions and its neighboring immediate geographic regions or microregions cargo matrix total volume and only agricultural bulk solids. These seven options vary from more to less comprehensive and are mostly based on real world railway projects (EDLP, 2022, 2016c; TPF-SENER, 2022a, 2022b; VALEC, 2015). The idea is to assess the best criteria to define the area of influence and potential cargo, balancing data volume and accuracy of results.

The heuristic is coded in Python language using the IDLE editor, which has interface with the GIS software ArcGIS Pro 3.0 (ESRI, 2023). Tests were executed in a PC with a 2.80-GHz Intel i7 processor and 16 GB of RAM.

4.2.1. Constructive heuristic

The constructive heuristic proposed to solve the railway network design model is shown in Figures 11, 12 and 13.

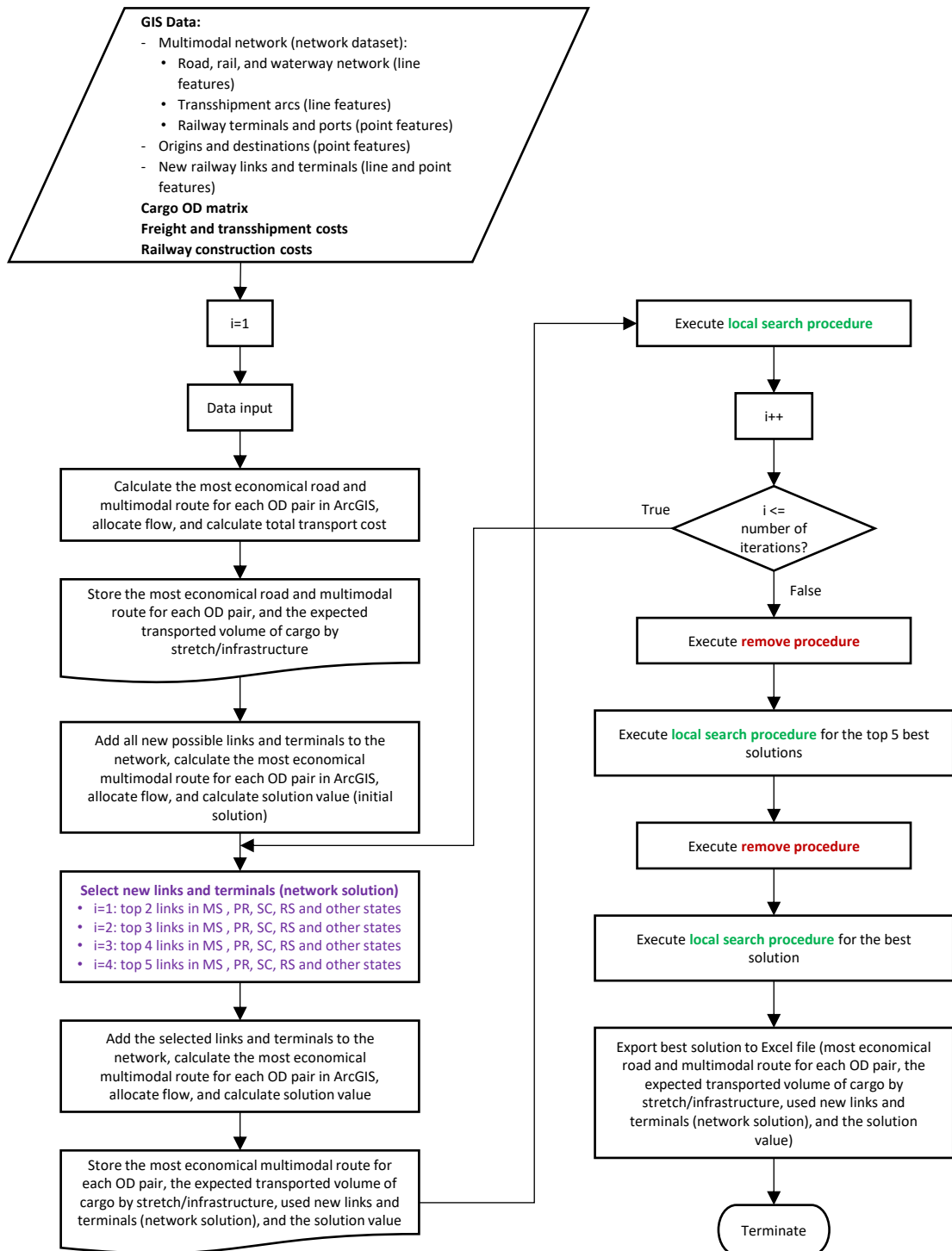


Figure 11. Framework of the proposed network railway design model.

Firstly, the initial solution is calculated, adding all new possible railway links and terminals to the Brazilian multimodal transportation network, and then calculating the most economical multimodal route for each O-D pair in ArcGIS Pro (ESRI, 2023). Thus, it is possible to find the links with the highest potential volume for domestic routes (Isler et al., 2021). The model considers all infrastructure with unconstrained capacity.

In the next step, the heuristic iteratively builds solutions with the top links, selecting at least two of the links with highest potential volume for domestic routes in each state. This criterion was determined since the objective of the new railway is to improve the domestic transportation.

For each solution, the heuristic adds the selected links and terminals to the Brazilian multimodal network and finds the most economical multimodal route for every O-D pair in ArcGIS Pro (ESRI, 2023). Then, it allocates the traffic between the road and multimodal routes and calculates the total transportation cost, the total railway construction cost (based only on the used links and terminals), and the solution value.

Afterwards, the heuristic performs a local search procedure (Figure 12) to find better solutions in the solution's neighborhood. In each iteration, adjacent links with high or medium potential volume for domestic routes are added to either the used links or the selected links, generating a new solution.

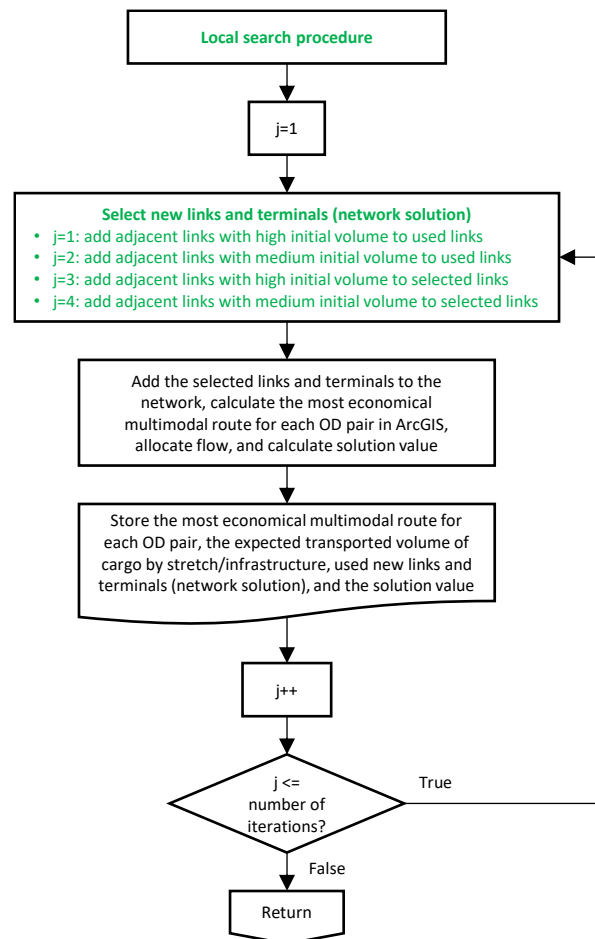


Figure 12. Framework of the local search procedure.

Next, a remove procedure is performed (Figure 13). It consists of removing non-used links and low volume links from the solution, to improve its benefit-cost ratio. The minimum link volume is 3.5 million tonnes annually, equivalent to six daily trains (Isler et al., 2021).

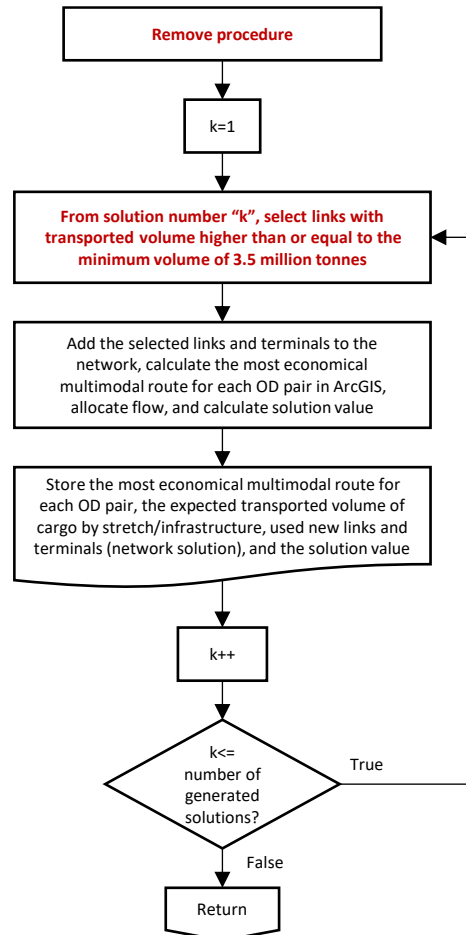


Figure 13. Framework of the remove procedure.

The next step is to perform the local search procedure in the top five best solutions, followed by another round of the remove procedure and by the final round of the local search procedure around the best solution.

Finally, the best solution values are exported to an Excel file. It consists of the most economical road and multimodal route for each O-D pair, the expected transported volume of cargo by stretch/infrastructure, the used new links' and terminals' volume, and the solution value.

Other rules were tested and generated the same or worse results. These other rules included creating solutions with links that transported at least the minimal volume of 3.5 million tonnes (Isler et al., 2021) or its multiple values (from 7 to 35 million tonnes); different weights for the costs and the benefits in the objective function; and other values for the railway link

construction cost b (R\$6.8*10⁶/km (Branco et al., 2020; ENEFER, 2018; Rocha, 2020) and R\$17.4*10⁶/km (Rocha, 2020; TPF-SENER, 2022b, 2022c)).

The codes for the constructive heuristic are shown in Appendix A (main code) and Appendix B (supporting functions).

4.2.2. Parameters

The railway network design model's parameters are detailed in the following paragraphs.

v_{ij} : The selected O-D cargo matrices were developed for the 2035 National Logistics Plan (PNL) in two different years: 2017 and expected for 2035 (EPL, 2021d). These O-D cargo matrices show the total volume transported between two traffic zones (O-D pairs), that can be a Brazilian municipality or an international zone, and by product group. The transported volume comprises intermediate flows, such as from producers to wholesalers, so it is higher than the production volume. There are six product groups: mineral bulk solids (iron ore), other mineral bulk solids (fertilizers and other minerals), bulk liquids (fuels and petrochemicals), agricultural bulk solids (soybean, maize, soybean meal, and sugar cane), containerizable general cargo, and non-containerizable general cargo (EPL, 2021a). It is assumed that all product groups can use multimodal transportation (roads, railways, and/or waterways). The 2017 data and the current transportation network are used to validate the model, while the proposed railway is based on 2035 referential estimation and the future network.

There are 5,589 origins and destinations (5,570 municipalities and 19 international zones), generating 2,573,701 O-D pairs in 2017 and 2,571,162 O-D pairs in 2035 (EPL, 2021d). However, calculating the most economical route in the ArcGIS Pro is a time consuming task, so the number of O-D pairs needs to be reduced (ESRI, 2023). The criteria used in this thesis are:

- O-D pairs are considered in only one direction, and the volume of the same two O-D pairs are summed up. The municipality with the lowest IBGE code number is considered the Origin (IBGE, 2021), and the other municipality is the Destination. For instance, consider the O-D pairs Sorriso (MT) - Chapecó (SC) and Chapecó - Sorriso. They are summarized in only one OD pair, Chapecó - Sorriso, as Chapecó's IBGE code number is 4204202 and Sorriso's is 5107925. If the O-D pairs exist in only one direction, then the Origin and the Destination are not altered.
- Origins or Destinations from the Center-West and South regions are utilized in the municipality level for interstate flows and are used in the immediate geographic region's

level for intrastate flows. The municipality with the highest total volume, both as Origin or Destination, is used to represent the immediate or intermediary geographic region. Origins or Destinations from the states adjacent to these regions (i.e., Rondônia, Amazonas, Pará, Tocantins, Bahia, Minas Gerais, and São Paulo) are used in the immediate geographic region's level for interstate flows with the Center-West and South regions and in the intermediary geographic region's level for the remaining flows. Origins or Destinations from the states that are not adjacent to the Center-West and South regions (i.e., Acre, Roraima, Amapá, Maranhão, Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe, Espírito Santo, and Rio de Janeiro) are used in the intermediary geographic region's level.

- O-D pairs from the Center-West and South regions with Origins and Destinations in the same immediate geographic area are discarded since there is at most only one new railway terminal per immediate geographic area. Intrastate flows from states out of the Center-West and South regions are also removed, as there is no traffic through the new railway's region.
- O-D pairs with annual total volume lower than 50,000 tonnes for Origins or Destinations from the Center-West and South regions or lower than 200,000 tonnes for the remaining O-D pairs are excluded. The 50,000 tonnes value is equivalent to three standard trains with 20 wagons of mixed types (carrying 1,600 tonnes) per month or one train composition with over 80 wagons (transporting over 7,000 tonnes) per bimester (Isler et al., 2021; Péra and Caixeta-Filho, 2021).

There were 2,916 O-D pairs in 2017 ($i = 452$, $j = 379$, with 59.1% of Brazil total volume and 69.2% of Center-West and South regions total volume) and 3,498 pairs in 2035 ($i = 502$, $j = 429$, with 63.9% of Brazil total volume and 73.5% of Center-West and South regions total volume) after applying the aforementioned criteria, allowing for a feasible computing time.

f_{ijk} : The transportation cost (in R\$/tonne of cargo) was estimated using linear models, described in the Equations (5) to (9). The linear models were chosen since logarithmic functions tend to calculate values lower than the actual values for small distances (João, 2021), and the segments in the multimodal network dataset used in ArcGIS Pro were split in several parts (ESRI, 2023).

$$f_{ijk} = fr_{ijk} + ff_{ijk} + fw_{ijk} + fm_{ijk} \quad (5)$$

$$fr_{ijk} = \alpha + \beta d_{ijk} \quad (6)$$

$$ff_{ijk} = 0.7(\alpha + \beta df_{ijk}) \quad (7)$$

$$fw_{ijk} = 0.4(\alpha + \beta dw_{ijk}) \quad (8)$$

$$fm_{ijk} = \gamma + \delta dm_{ijk} + hs \quad (9)$$

where,

f_{ijk} = transportation cost from origin i to destination j using mode k ($k \in \{1 = road, 2 = multimodal\}$) (in R\$/tonne of cargo);

fr_{ijk} = road freight cost between origin i and destination j using road and maritime network ($k=1$) or multimodal network ($k=2$) (in R\$/tonne of cargo);

α = y-intercept of the linear function for the road freight cost;

β = slope of the linear function for the road freight cost;

d_{ijk} = distance traveled by road between origin i and destination j using the most economical road and maritime route ($k=1$) or the most economical multimodal route ($k=2$) (in km);

ff_{ijk} = railway transportation cost between origin i and destination j using the multimodal network ($k=2$) (in R\$/tonne of cargo);

df_{ijk} = distance traveled by railway between origin i and destination j using the most economical multimodal route ($k=2$) (in km);

fw_{ijk} = waterway transportation cost between origin i and destination j using the multimodal network ($k=2$) (in R\$/tonne of cargo);

dw_{ij2} = distance traveled by waterway between origin i and destination j using the most economical multimodal route ($k=2$) (in km);

fm_{ijk} = maritime transportation cost between origin i and destination j using the most economical road and maritime route ($k=1$) or the most economical multimodal route ($k=2$) (in R\$/tonne of cargo);

γ = y-intercept of the linear function for the maritime freight cost;

δ = slope of the linear function for the maritime freight cost;

dm_{ijk} = distance traveled by sea between origin i and destination j using the most economical road and maritime route ($k=1$) or the most economical multimodal route ($k=2$), for international flows (in km);

hs = handling service fee at the port (in R\$/tonne of cargo).

The α and β parameters' values were estimated using a linear regression with the least squares method of the 2017 road freight cost data from SIFRECA¹⁴ (ESALQ-LOG, 2022) of soybean, maize, sugar, ethanol, and fertilizers, presented in Table 11. The year 2017 was selected since it is the reference year for the PNL-2035, which is the source of the O-D cargo matrices and of the transportation network shapefiles used in this thesis.

Table 11. Road freight cost equation and statistical significance tests.

Statistical tests	Linear regression
Estimated equation	$fr_{ij1} = 35.18 + 0.098573d_{ij1}$
R-squared (R^2)	0.83
P-value	<0.01%
Sample size	23,011 freight records

Source: prepared by the author, based on data from SIFRECA (ESALQ-LOG, 2022).

The d_{ijk} , df_{ijk} , dw_{ijk} and dm_{ijk} distances were calculated by the Route analysis module of ArcGIS Pro (ESRI, 2023), using the road and maritime transportation network for $k=1$ and the multimodal transportation network for $k=2$. The transportation networks are described in the section 4.2.3.

The railway freight cost from origin i to destination j is estimated as 70% of the road freight cost from origin i to destination j , while the waterway freight cost is estimated as 40% of the road freight cost (Branco et al., 2020; Rocha, 2020). However, due to the ArcGIS Pro structure (ESRI, 2023), the railway freight cost and the waterway freight cost are calculated using the railway and waterway traveled distances from origin i to destination j , respectively, instead of the road traveled distance from origin i to destination j .

For iron ore, the railway freight cost is equal to the Equation (10), since its pricing is considerably lower than other products (ANTT, 2020):

$$ff_{ij2} = 9.93 + 0.0366d_{ij2} \quad (10)$$

For international Origins or Destinations, the parameters' values of the linear function to estimate the maritime freight cost are $\gamma=49.917$ and $\delta=0.002411$ (Rocha, 2020). The handling service fee hs is R\$ 26.90/t, calculated as the average of Brazilian ports' values (Silva-Neto, 2018).

¹⁴ "SIFRECA is a specialized system that collects Brazilian real freight prices for numerous commodities and routes <http://sifreca.esalq.usp.br/>" (Branco et al., 2020) in a monthly basis. The road freight prices include tolls and taxes (ICMS, PIS and COFINS).

p_{ijk} : The flow assignment technique used in this thesis follows a deterministic rule to reflect the variable perception of transportation costs and the traffic spreading across different modes and routes (Maia and Couto, 2013). Costs are arguably the most important decision factor, but the modal choice also depends on availability, distance, quantity, value of the goods, trip time, and quality tradeoffs (Thompson and Sondhi, 2002).

Thus, if the difference between the road transportation cost f_{ij1} and the multimodal transportation cost f_{ij2} is less than or equal to 1%, then 90% of the volume between origin i and destination j is transported by road ($p_{ij1} = 0.90$), which provides a faster service with higher quality, and the remaining 10% is transported by multimodal transportation ($p_{ij2} = 0.10$). Similarly, if the difference between the road transportation cost f_{ij1} and the multimodal transportation cost f_{ij2} is between 1% and 10%, then 30% of the volume between origin i and destination j is transported by road ($p_{ij1} = 0.30$) and 70% of the volume is transported by multimodal transportation ($p_{ij2} = 0.70$), and so on. Lastly, if there is no multimodal option, then 100% of the volume is transported by road ($p_{ij1} = 1.00$).

b : The average construction cost b to build railway links is estimated at R\$25.2*10⁶/km (Isler et al., 2022). Other values for b are R\$6.8*10⁶/km (Branco et al., 2020; ENEFER, 2018; Rocha, 2020), based on estimates for FICO, FNS and FIOL, and R\$17.4*10⁶/km (Rocha, 2020; TPF-SENER, 2022b, 2022c), calculated from Ferrogrão and Nova Ferroeste. The adopted value is the highest and was chosen as a worst-case scenario.

e_l : The extension of the potential railway links of the new railway e_l (in km) is calculated by ArcGIS Pro (ESRI, 2023).

t : The railway terminal building cost t is estimated at R\$ 34.5*10⁶ (Plaza et al., 2020; TPF-SENER, 2022a, 2022c).

The first level model's parameters are summarized in Table 12.

Table 12. Parameters of the railway network design model.

Parameter(s)	Value(s)	Source(s)
v_{ij} (transported volume)	2017 and 2035 O-D cargo matrices (in tonnes)	EPL (2021d)
f_{ijk} (transportation cost)	Estimated for each O-D pair using a linear regression of the 2017 road freight cost (in R\$/tonne)	SIFRECA (ESALQ-LOG, 2022)
d_{ijk} , df_{ijk} , dw_{ijk} and dm_{ijk} (distances)	Calculated by the Route analysis module for each O-D pair (in km)	ArcGIS Pro (ESRI, 2023)
hs (handling service fee)	R\$ 26.90/tonne	Silva-Neto (2018)
b (average construction cost)	R\$25.2*10 ⁶ /km	Isler et al. (2022)
e_l (extension of the potential railway links)	Calculated by the Route analysis module for each link (in km)	ArcGIS Pro (ESRI, 2023)
t (railway terminal building cost)	R\$ 34.5*10 ⁶	Plaza et al. (2020); TPF-SENER (2022c, 2022b)

4.2.3. Brazilian multimodal transportation network

To represent the current and future Brazilian multimodal transportation network in ArcGIS Pro (ESRI, 2023), this thesis uses the 2017 and the 2035 shapefiles of the PNL-2035 (EPL, 2021c), since they are an updated, complete and reliable version of this network (EPL, 2021a). These shapefiles contain the most relevant Brazilian transportation infrastructures (roads, railways, waterways, sea routes, ports, and transshipment terminals) that transported goods either in the 2017 or 2035 scenarios of the PNL-2035 (EPL, 2021a, 2021c).

Due to computing time limitations and to the studied problem's structure, the following modifications and adjustments were carried out:

- Global type 12 denotes waterway terminals and ports, and global type 13 represents the railway terminals. Identical records representing the same port or terminal were deleted.
- Brazilian's origins and destinations are represented by the municipality's virtual geographic center (point feature class) and are connected only to the road network.
- The 19 international zones were represented by only one point each. The selected points were the ones that can be reached by a higher number of routes or that received the highest volume in the PNL-2035. Bolivia is reached by road, Paraguay and Argentina are accessed by the Paraguay-Paraná waterway, and the other 16 international zones are reached by sea routes.
- Railway terminals are connected to railways and roads, while waterway terminals and ports are connected to waterways, sea routes and roads.

All non-existent connections (origins, destinations, railway terminals, and ports to roads; railway terminals to railways; ports to waterways, cabotage, and sea routes) were created using ArcGIS Pro tools “Near” and “Points to line” (ESRI, 2023). Topology rules were created to solve overlapping and intersecting problems that prevented an accurate use of the network. The multimodal network is built in ArcGIS Pro as a network dataset, with four groups (road, rail, waterway, and sea) and the transportation cost as the cost function (ESRI, 2023). The cost function for each group is detailed in section 4.2.2. The ArcGIS Pro Route solver calculates the minimum cost route between an origin and a destination through either the road/maritime or the multimodal network. For the road/maritime network, the maritime network is only available for international destinations (ESRI, 2023).

The future 2035 network considers the implementation of the projects selected in PNL-2035 “Scenario 9 - Main opportunities + Referential”, since they generated the most positive impacts within a restricted budget (EPL, 2021a). Almost all projects are the same from “Scenario 1 – Projects in progress”. The most improved indicators were average freight transportation cost, weighted average passenger transportation time, volume of greenhouse gas (GHG) emissions, and safety index (EPL, 2021a). The majority of the railway projects were also selected in other studies (Branco et al., 2020; Péra, 2022; Rocha, 2020; Silva-Neto, 2018). The main considered projects are (EPL, 2021a; Governo de Mato Grosso do Sul, 2022; PPI, 2021):

- Railways:
 - West-East Integration Railway – FIOLE (EF-334): from Ilhéus, in the state of Bahia (BA), to Figueirópolis (TO), passing by Caetité (BA) and Barreiras (BA);
 - Center-West Integration Railway – FICO (EF-354): from Mara Rosa (GO) to Lucas do Rio Verde (MT), passing by Água Boa (MT);
 - Ferrogrão (EF-170);
 - North-South Railway - FNS (EF-151): from Aguiarnópolis, in the state of Tocantins (TO), to Chapecó (SC), passing by Palmas (TO), Uruaçu (GO), Anápolis (GO), Ouro Verde (GO), São Simão (GO), Santa Vitória (MG), Iturama (MG), Ouroeste, in the state of São Paulo (SP), Estrela D’Oeste (SP), and Cascavel (PR);
 - Transcontinental Railway (EF-354): from Sapezal (MT) to Porto Velho, in the state of Rondônia (RO);
 - New Northeastern Railway – NTN: from Eliseu Martins, in the state of Piauí (PI), to the ports of Pecém, in the state of Ceará (CE), and Suape, in the state of Pernambuco (PE);
 - Nova Ferroeste (EF-484): from Dourados (MS) to Cascavel (PR);
 - Reactivation of Rumo Malha Oeste Railway from Corumbá (MS) to Mairinque (SP) and of

stretches of Rumo Malha Sul Railway;

- Roads:
 - Improvements in highways BR-163 (MT), MT-407, BR-060/153/262 (DF/GO/MG), BR-040 (DF/GO/MG), BR-470 (SC), BR-282/153 (SC), SC-412, BR-153/080/414 (GO/TO), BR-116/493 (RJ/MG), and BR-116/465/101 (SP/RJ);
 - Concession and improvements in the Paraná Integrated Highways (BR-153/158/163/272/277/369/373/376/476 and other relevant Paraná state highways).

The Brazilian 2017 multimodal transportation network is shown in Figure 14.



Figure 14. Brazilian 2017 multimodal transportation network.

Source: EPL (2021c).

Table 13 compares the modal split - in % of net tonne-kilometer (TKU) - obtained for the 2017 O-D cargo matrix using the 2017 multimodal transportation network in ArcGIS Pro (EPL, 2021d; ESRI, 2023) with the results from PNL-2035 (EPL, 2021a).

Table 13. 2017 estimated modal split (in %TKU).

	Domestic		International		Total		PNL-2035	
	TKU (billion)	% TKU	TKU (billion)	% TKU	TKU (billion)	% TKU	TKU (billion)	% TKU
Railway	105.39	15.3%	201.46	41.7%	306.85	26.2%	414.12	17.7%
Waterway/Cabotage	277.11	40.3%	73.13	15.1%	350.23	29.9%	346.09	14.8%
Road	304.93	44.4%	208.16	43.1%	513.09	43.8%	1,549.84	66.2%
Total	687.43		482.75		1,170.18		2,310.05	

Sources: EPL (2021d, 2021a) and results from this thesis.

Since the 2017 O-D cargo matrix used in this thesis is a reduced version of the one used in PNL-2035, the results are not directly comparable. However, the O-D pairs from the Center-West and South regions in the same immediate geographic area and the intrastate flows from states out of these regions were discarded. As these O-D pairs use only road mode, the results obtained are satisfactory and validate the implemented model.

Figure 15 shows the Brazilian 2035 multimodal transportation network. In Table 14, there is a comparison between the modal splits obtained for the 2035 O-D cargo matrix using the 2035 multimodal transportation network in ArcGIS Pro (EPL, 2021d; ESRI, 2023) with the results from PNL-2035 (EPL, 2021a). Again, due to the utilization of a reduced version of the PNL-2035 cargo matrix, the results are not directly comparable. Nevertheless, the implemented model generated reasonable results.

Table 14. 2035 estimated modal split (in %TKU).

	Domestic		International		Total		PNL-2035	
	TKU (billion)	% TKU	TKU (billion)	% TKU	TKU (billion)	% TKU	TKU (billion)	% TKU
Railway	226.00	23.2%	427.71	49.2%	653.71	35.4%	1,518.67	43.0%
Waterway/Cabotage	312.04	32.0%	99.11	11.4%	411.15	22.3%	497.45	14.1%
Road	437.99	44.9%	341.99	39.4%	779.98	42.3%	1,466.70	41.5%
Total	976.03		868.81		1,844.84		3,482.82	

Sources: EPL (2021d, 2021a) and results from this thesis.

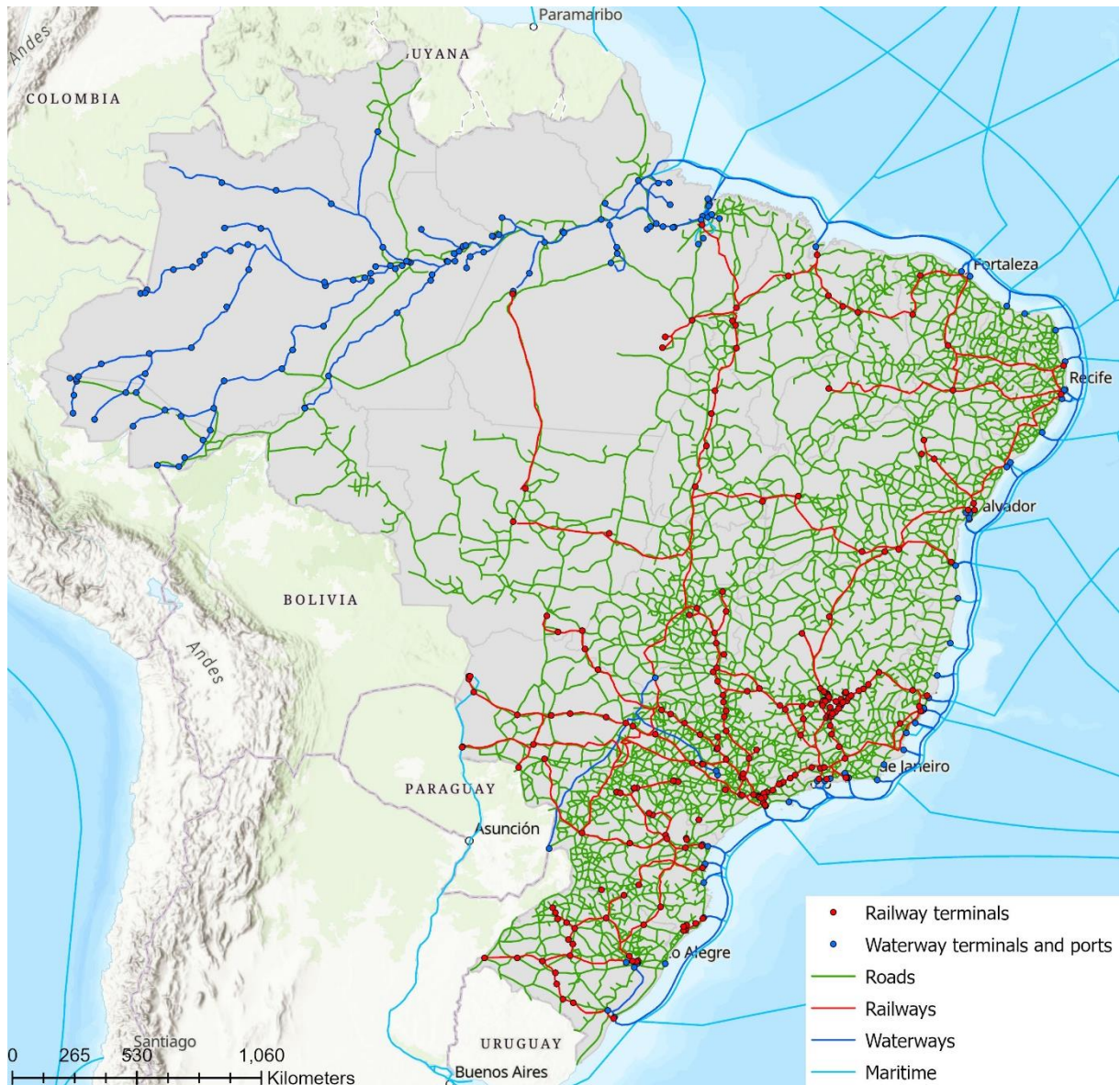


Figure 15. Brazilian 2035 multimodal transportation network.

Source: EPL (2021c).

4.3. Brazil's agricultural products logistic network improvement model

The second level is a linear programming problem developed to optimize the Brazilian agricultural products logistic network, calculating the Origin-Destination (O-D) flows and storage volumes that minimize the total logistic and product cost and the carbon dioxide (CO₂) emissions. The CO₂ is the main GHG and its reduction is the objective of several studies (Branco et al., 2020; Maia and Couto, 2013; Péra, 2022; Plaza et al., 2020; Rocha, 2020; Rodrigue, 2020). The model uses the ArcGIS Pro Route solver to find the most economical road or multimodal route in the Brazilian multimodal transportation network (ESRI, 2023).

The problem can be summarized as: let the origins o ($o = 1, \dots, i$) be the Brazilian municipalities with production of p ($p \in \{1 = \text{maize}, 2 = \text{soybean}, 3 = \text{soybean meal}\}$). Every month m ($m = 1, \dots, 12$), the produced volume of each product p can be transported through the Brazilian road or multimodal network directly from the origins o to: the destinations d ($d = 1, \dots, k$), that are the municipalities with animal feed facilities, soybean crushing plants, and other significant domestic demand generators (transported volume x_{podm}); the exporting ports e ($e = 1, \dots, l$) (transported volume x_{poem}); or to the warehouses j ($j = 1, \dots, n$), located in the same state than the origin o (transported volume $x_{poj m}$) (ESALQ-LOG, 2020; João, 2021; Péra, 2022; Rocha, 2020; Silva-Neto, 2018). Intrastate flows of maize, soybean, soybean meal, and other essential products are generally ICMS¹⁵ free, while interstate sales have ICMS tax of around 12%, which hinders the usage of warehouses from other states (ESALQ-LOG, 2020; Guimarães, 2022; Rezende, 2022).

From the warehouse j , the cargo is moved either to a destination d ($x_{pjd m}$) or to exporting ports e (x_{pjem}) in the following months, using the Brazilian road or multimodal network. Imported cargos go directly from the entry points in Brazil i ($i = 1, \dots, q$) to the demand points d ($x_{pid m}$), with $p \in \{1 = \text{maize}, 2 = \text{soybean}\}$ (ESALQ-LOG, 2020; João, 2021; Péra, 2022; Rocha, 2020; Silva-Neto, 2018). The objective of the Brazil's agricultural products logistic network improvement model is to find the transported volumes x_{podm} , x_{poem} , $x_{poj m}$, $x_{pjd m}$, x_{pjem} , and $x_{pid m}$ (in tonnes), the monthly stored volume by product and by warehouse y_{pjm} (in tonnes), and the storage capacity increase volume by warehouse z_j (in tonnes) that minimizes the total annual logistics costs (sum of freight cost, monthly storage fee, and storage handling and drying fee), product cost (sum of product price and taxes), and CO₂ emissions.

The mathematical model is as follows:

¹⁵ ICMS is the Tax on the Circulation of Goods and Services.

$$\begin{aligned}
\min_{x,y,z} Z = & \sum_{p=1}^3 \sum_{o=1}^i \sum_{d=1}^k \sum_{m=1}^{12} x_{podm} \{ \alpha [f_{podm} + pro_{pom}(1 + txo_{pod})] + \beta em_{od} \} \\
& + \sum_{p=1}^3 \sum_{o=1}^i \sum_{e=1}^l \sum_{m=1}^{12} x_{poem} \{ \alpha [f_{poem} + pro_{pom}] + \beta em_{oe} \} \\
& + \sum_{p=1}^3 \sum_{o=1}^i \sum_{j=1}^n \sum_{m=1}^{12} x_{poj m} \{ \alpha [f_{poj m} + hd_j] + \beta em_{oj} \} \\
& + \sum_{p=1}^3 \sum_{j=1}^n \sum_{d=1}^k \sum_{m=1}^{12} x_{pjdm} \{ \alpha [f_{pjdm} + prj_{pjm}(1 + txj_{pjd})] + \beta em_{jd} \} \\
& + \sum_{p=1}^3 \sum_{j=1}^n \sum_{e=1}^l \sum_{m=1}^{12} x_{pjem} \{ \alpha [f_{pjem} + prj_{pjm}] + \beta em_{je} \} \\
& + \sum_{p=1}^3 \sum_{i=1}^q \sum_{d=1}^k \sum_{m=1}^{12} x_{pidm} \left\{ \alpha \left[f_{pidm} + \frac{pri_{pim}}{(1 - txi)} \right] + \beta em_{id} \right\} \\
& + \sum_{p=1}^3 \sum_{j=1}^n \sum_{m=1}^{12} \alpha y_{pjm} ms_j
\end{aligned} \tag{11}$$

subject to

$$\sum_{d=1}^k x_{podm} + \sum_{e=1}^l x_{poem} + \sum_{j=1}^n x_{poj m} = sup_{pom} \quad p = 1,2,3; o = 1, \dots, i; m = 1, \dots, 12 \tag{12}$$

$$\sum_{o=1}^i x_{poem} + \sum_{j=1}^n x_{pjem} = exp_{pem} \quad p = 1,2,3; e = 1, \dots, l; m = 1, \dots, 12 \tag{13}$$

$$\sum_{o=1}^i x_{podm} + \sum_{j=1}^n x_{pjdm} + \sum_{i=1}^q x_{pidm} = dem_{pdm} \quad p = 1,2,3; d = 1, \dots, k; m = 1, \dots, 12 \tag{14}$$

$$\sum_{d=1}^k x_{pidm} \leq imp_{pim} \quad p = 1,2,3; i = 1, \dots, q; m = 1, \dots, 12 \tag{15}$$

$$y_{pjm} = isv_{pj} + \sum_{o=1}^i x_{poj m} - \sum_{d=1}^k x_{pjdm} - \sum_{e=1}^l x_{pjem} \quad p = 1,2,3; j = 1, \dots, n; m = 1 \tag{16}$$

$$y_{pjm} = y_{pjm-1} + \sum_{o=1}^i x_{poj m} - \sum_{d=1}^k x_{pjdm} - \sum_{e=1}^l x_{pjem} \quad p = 1,2,3; j = 1, \dots, n; \\ m = 2, \dots, 12 \tag{17}$$

$$\sum_{p=1}^3 y_{pjm} \leq msc_j + z_j \quad j = 1, \dots, n; m = 1, \dots, 12 \quad (18)$$

where,

α = weight of the total logistic and product cost component;

f_{podm} = freight cost from origin o to destination d for product p on month m (in R\$/tonne of cargo);

pro_{pom} = price of product p in origin o on month m (in R\$/tonne of cargo);

txo_{pod} = taxes on price of product p from origin o to destination d (in %);

β = weight of the CO₂ emissions component;

em_{od} = CO₂ emission rate from origin o to destination d (in kgCO₂/tonne of cargo);

f_{poem} = freight cost from origin o to exporting port e for product p on month m (in R\$/tonne of cargo);

em_{oe} = CO₂ emission rate from origin o to exporting port e (in kgCO₂/tonne of cargo);

$f_{poj m}$ = freight cost from origin o to warehouse j for product p on month m (in R\$/tonne of cargo);

hd_j = storage handling and drying fee of warehouse j (in R\$/tonne of cargo);

em_{oj} = CO₂ emission rate from origin o to warehouse j (in kgCO₂/tonne of cargo);

$f_{pjd m}$ = freight cost from warehouse j to destination d for product p on month m (in R\$/tonne of cargo);

prj_{pjm} = price of product p in warehouse j on month m (in R\$/tonne of cargo);

txj_{pjd} = taxes on price of product p from warehouse j to destination d (in %);

em_{jd} = CO₂ emission rate from warehouse j to destination d (in kgCO₂/tonne of cargo);

f_{pjem} = freight cost from warehouse j to exporting port e for product p on month m (in R\$/tonne of cargo);

em_{je} = CO₂ emission rate from warehouse j to exporting port e (in kgCO₂/tonne of cargo);

$f_{pid m}$ = freight cost from entry point i to destination d for product p on month m (in R\$/tonne of cargo);

pri_{pim} = price of product p in entry point i on month m (in R\$/tonne of cargo);

txi = taxes on price of imported products (in %);

em_{id} = CO₂ emission rate from entry point i to destination d (in kgCO₂/tonne of cargo);

ms_j = monthly storage fee of warehouse j (in R\$/tonne of cargo);

sup_{pom} = total supply volume by origin o for product p on month m (in tonnes of cargo);

exp_{pem} = total exported volume by exporting port e for product p on month m (in tonnes of cargo);

dem_{pdm} = total demanded volume by destination d for product p on month m (in tonnes of cargo);

imp_{pim} = maximum imported volume by entry point i for product p on month m (in tonnes of cargo);

isv_{pj} = initial stored volume of product p in warehouse j (in tonnes of cargo);

msc_j = maximum storage capacity of warehouse j (in tonnes of cargo).

The objective function in Equation (11) minimizes the sum of total annual logistics and product costs and CO₂ emissions. The constraint in Equation (12) ensures that all volume produced of each product in each month is transported from an origin to a destination, an exporting port, or a warehouse. The constraint in Equation (13) guarantees that all volume of each product demanded by an exporting port in each month is shipped from an origin or a warehouse. Similarly, the constraint in Equation (14) assures that all volume of each product demanded by a destination in each month is sent from an origin or a warehouse. The constraint in Equation (15) secures that the monthly imported volume of each product does not exceed the maximum available volume.

The constraints in Equations (16) and (17) ensures that the final stored volume of each product in each warehouse every month is equal to the difference between the sum of the initial stored volume and the volume received from the origins and the sum of the volume sent to the destinations and exporting ports. Finally, the constraint in Equation (18) guarantees that the monthly stored volume in each warehouse is lower or equal to the sum of the warehouse's maximum storage capacity and the increased volume.

As in the railway network design model, the 2017 data and the current transportation network are used to validate the model, while the 2035 estimated data and the future network are applied to find the optimal configuration for the Brazilian's agricultural products logistic network. The 2020 data were used as an estimation for the 2035 freight costs and product prices and were the starting point to calculate the 2035 supply and demand values. For this thesis, the relative values between the products' monthly freight and product costs are more important than their absolute value, thus there will be no monetary adjustments due to inflation. The year 2020 was selected since it was the most recent year with complete and official data during the data collection for this thesis. In addition, 2020 is one of the reference years for the PNL-2035.

In addition, as this is a strategic level problem, there will be no capacity constraint in the used transportation infrastructures, such as railway and waterway terminals and ports. The limited volumes in the exporting ports or in the entry points are due to a demand/supply constraint, and not because of their capacity. For the same reason, the cost to expand the warehouses' static storage capacity is not considered.

The 2017 validation scenarios use only soybean and maize, while the 2035 scenarios include soybean meal. Other scenarios evaluate different weights for the components of the objective function and the effects of the "BR do Mar" and of lower railway freight costs.

The mathematical model was built in the software General Algebraic Modelling System (GAMS), using CPLEX as the solver (GAMS, 2023). The code for the model is shown in Appendix C. The ArcGIS Pro was used to find the most economical road and multimodal routes for each O-D pair (ESRI, 2023).

4.3.1. Parameters

The Brazil's agricultural products logistic network improvement model's parameters are detailed below.

α and β : the weights of each component of the objective function will vary depending on the scenario.

f_{podm} , f_{poem} , $f_{poj m}$, f_{pjdm} , f_{pjem} , and f_{pidm} : Similar to the railway network design model (section 4.2.2), the road freight costs (in RS/tonne of cargo) were estimated using linear regression with the least squares method of the 2017 and 2020 road freight cost data from SIFRECA (ESALQ-LOG, 2022).

The parameters' values for the 2017 and 2020 road freight costs equations are shown in Tables 15 and 16, respectively. The 2020 values are used as a proxy for the 2035 freight costs, as it was the most recent year with complete and official data during the data collection for this thesis.

Table 15. Parameters' values for the 2017 road freight cost equations and statistical significance tests.

Product	Month	y-intercept	Slope	R-squared	P-value	Sample size
Soybean	1	27.34	0.10	0.91	0.00	497
	2	36.62	0.12	0.90	0.00	960
	3	41.89	0.11	0.90	0.00	1,245
	4	32.35	0.11	0.91	0.00	820
	5	29.55	0.11	0.92	0.00	745
	6	24.20	0.11	0.93	0.00	862
	7	30.82	0.11	0.89	0.00	610
	8	35.03	0.12	0.88	0.00	546
	9	33.66	0.11	0.79	0.00	423
	10	34.01	0.10	0.91	0.00	230
	11	26.62	0.11	0.86	0.00	257
	12	20.96	0.10	0.94	0.00	142
Maize	1	15.74	0.09	0.93	0.00	174
	2	27.30	0.11	0.93	0.00	108
	3	23.31	0.12	0.94	0.00	256
	4	24.60	0.11	0.94	0.00	93
	5	17.45	0.10	0.97	0.00	130
	6	29.56	0.11	0.94	0.00	448
	7	35.42	0.11	0.92	0.00	866
	8	37.01	0.12	0.89	0.00	929
	9	34.18	0.11	0.90	0.00	788
	10	40.90	0.11	0.89	0.00	679
	11	34.06	0.11	0.92	0.00	619
	12	29.21	0.11	0.92	0.00	505
Soybean and maize		33.18	0.11	0.90	0.00	12,932

Source: prepared by the author, based on data from SIFRECA (ESALQ-LOG, 2022).

Table 16. Parameters' values for the 2020 road freight cost equations and statistical significance tests.

Product	Month	y-intercept	Slope	R-squared	P-value	Sample size
Soybean	1	14.67	0.12	0.92	0.00	297
	2	35.74	0.12	0.92	0.00	535
	3	42.30	0.11	0.89	0.00	816
	4	40.24	0.12	0.90	0.00	942
	5	29.55	0.12	0.91	0.00	770
	6	24.76	0.12	0.91	0.00	787
	7	21.59	0.13	0.91	0.00	583
	8	35.13	0.11	0.76	0.00	304
	9	20.01	0.14	0.83	0.00	277
	10	15.82	0.13	0.83	0.00	164
	11	13.11	0.12	0.83	0.00	71
	12	14.65	0.10	0.86	0.00	25
Maize	1	21.06	0.10	0.85	0.00	120
	2	17.10	0.13	0.89	0.00	121
	3	39.43	0.10	0.90	0.00	141
	4	37.53	0.11	0.95	0.00	410
	5	34.78	0.11	0.94	0.00	416
	6	38.13	0.12	0.89	0.00	630
	7	32.29	0.13	0.94	0.00	1,104
	8	39.03	0.12	0.91	0.00	1,129
	9	35.33	0.11	0.92	0.00	976
	10	30.22	0.11	0.93	0.00	697
	11	26.83	0.11	0.93	0.00	706
	12	25.62	0.11	0.92	0.00	563
Soybean and maize		32.00	0.12	0.90	-	12,584
Soybean meal	1 st semester	36.71	0.12	0.88	0.00	227
	2 nd semester	40.87	0.11	0.81	0.00	199

Source: prepared by the author, based on data from SIFRECA (ESALQ-LOG, 2022).

It is assumed that the relation (%) between road freight and multimodal freight is constant, given that rail and waterways' freight price depend on the road freight value to compete (Branco et al., 2020; Rocha, 2020). Thus, the most economical road and multimodal routes are found in ArcGIS Pro (ESRI, 2023) using the linear regression equation for soybean and maize for the whole year (2017 or 2020). Then the road freight cost for each product, each O-D pair, and in each month is calculated using the road distance of the most economical road route and the linear regression equation parameters for that product and month. The multimodal freight is calculated

using the estimated relation between the most economical road freight and most economical multimodal freight for each O-D pair. For origins and destinations in the same municipality, it is assumed that the traveled distance is 10 km by road.

The 2017 (current) and 2035 (future) Brazilian multimodal transportation networks (roads, railways, waterways, ports, and transshipment terminals) and the new proposed railway are the same of the first level model (sections 4.2.3 and 5.1.1), as well as the ArcGIS Pro Route solver used to find the most economical road and multimodal routes for each O-D pair (ESRI, 2023). Origins, destinations, railway terminals, and ports are directly connected to the road network; thus, every route has a road stretch, even if it is a small one to reach a terminal or a port (pre-haul).

pro_{pom}, ***prj_{pjm}*** and ***pri_{pim}***: The monthly price of products for 2017 and 2020 were available for the main producing municipalities (53 for maize, 46 for soybean, and 14 for soybean meal) (Safra&Mercado, 2022b). To allocate the prices in all origins and warehouses, the following order was used: same municipality, same microregion, same mesoregion, same state, and same region (IBGE, 2021) of the available data.

For the imported products, the product price was calculated by dividing the total imported value (in US\$) by the total imported volume and multiplied by the monthly exchange rate in 2017 and 2020 (BACEN, 2023; MDIC, 2023). The 2020 values are used as a proxy for the 2035 products' price as it was the most recent year with complete and official data during the data collection for this thesis.

txo_{pod}, ***txj_{pjd}*** and ***txi***: The taxes system in Brazil is complex. There are different rules for different products, different tax rates for different states and for intrastate and interstate operations, and taxes are calculated either in the “inside” or in the “outside”. It heavily influences purchase decisions, especially for large volumes such as those of the agricultural products.

In this thesis, only the ICMS is considered. For intrastate sales and for sales to export markets, the ICMS rate is 0%. For interstate sales, the ICMS rate is 12% when destinations are in the states of Minas Gerais, Paraná, Rio de Janeiro, Rio Grande do Sul, Santa Catarina, and São Paulo; and 7% for all other states. In addition, there is the “Convênio 100/97” agreement, in which the calculation base is reduced by 30% when maize, soybean, soybean meal, and other essential products are sold to producers, cooperatives, the animal feed industry, or an official state agency for the promotion of agricultural development. Warehouses are not included in the “Convênio 100/97” and must pay the full ICMS rate. The “Convênio 100/97” has been approved until the end of 2025 (ESALQ-LOG, 2020; Guimarães, 2022; Rezende, 2022).

The ICMS is calculated internally, as shown in Equation (19), which already considers the reduction in the calculus base.

$$txo_{pod} = txj_{pjd} = \frac{0.7}{1 - ICMS} \quad (19)$$

For imported products, the ICMS is equal to 4%, although it was temporarily exempted in 2020 and 2021. Furthermore, it is generally 0% for products imported from the Mercosur, which is the main origin of the imported agricultural products; so, this thesis will consider that $txi = 0$ (ACSURS, 2022; ESALQ-LOG, 2020; FAZCOMEX, 2023).

The current values are used as a proxy for the 2035 ICMS rates.

em_{od} , em_{oe} , em_{oj} , em_{jd} , em_{je} , and em_{id} : The CO₂ emission rate (in kgCO₂/tonne of cargo) is calculated for each route, considering the distance traveled in each mode and the following rates: 0.03914 kgCO₂/t.km for road mode, 0.01975 kgCO₂/t.km for railways, and 0.00790 kgCO₂/t.km for waterways and cabotage (Rocha, 2020). The distance traveled in each mode for the most economical road and multimodal routes for each O-D pair is calculated by the Route solver of ArcGIS Pro (ESRI, 2023).

hd_j and ms_j : The storage handling and drying fee and the monthly storage fee were estimated for the main states using data from SIARMA (ESALQ-LOG, 2019, 2020), as shown in Table 17. For the remaining states, the fees were the same as the states in the same region. The storage handling and drying fee is charged when the cargo enters the warehouse, and the monthly storage fee is accounted for at the end of every month.

The current values are used as a proxy for the 2035 storage fees.

Table 17. Storage handling and drying fee and monthly storage fee for the main Brazilian states.

State	Storage handling and drying fee (R\$/t)	Monthly storage fee (R\$/t)
GO	25.00	5.50
MT	25.00	5.50
MS	26.26	5.00
PR	26.26	5.00
SC	30.50	5.80
RS	30.50	5.80
BA	28.00	6.00
TO	28.00	6.00
MG	28.00	6.00

Source: prepared by the author, based on data from SIARMA (ESALQ-LOG, 2019, 2020).

sup_{pom} and **dem_{pdm}** : The maize and soybean annual production volumes (IBGE, 2022b) were combined with the monthly harvest schedule by state (CONAB, 2022a; SANCHES, 2018) to find the supply volume by origin, product, and month. The following rules were applied to calculate the harvest percentage by month (SANCHES, 2018):

- For a harvest lasting two months, the production is divided in 50% in each month.
- For a harvest lasting three months, the production is divided in 20%, 60%, and 20%.
- For a harvest lasting four months, the production is divided in 10%, 40%, 40%, and 10%.
- For a harvest lasting five months, the production is divided in 10%, 20%, 40%, 20%, and 10%.
- For a harvest lasting six months, the production is divided in 10%, 20%, 20%, 20%, 20%, and 10%.

The soybean domestic consumption and the soybean meal production volumes are equivalent to the soybean annual crushing capacity, grouped by municipality of the crushing facility (ABIOVE, 2023; Ary Oleofar, 2023), and adjusted by the annual volume (ABIOVE, 2023; Safras&Mercado, 2022a). The maize and soybean meal domestic consumption volume were calculated as the number of poultry and pigs per municipality (IBGE, 2022c), multiplied by the consumption of each animal (Santos-Filho et al., 2018), and adjusted by the annual consumption volume (Safras&Mercado, 2022a). A chicken needs 3.44 kg of maize and 1.64 kg of soybean meal, while a swine requires 235 kg of maize and 66 kg of soybean meal (Santos-Filho et al., 2018). The monthly volume variation in the soybean crushing industry and in the poultry and pork industries is around 10% (ABIOVE, 2023; ESALQ-LOG, 2020), so this thesis is going to assume that the monthly volume is constant.

The maize and soybean production volume and the maize and soybean meal domestic consumption volume were grouped by microregion for the Center-West and South region states (Mato Grosso, Mato Grosso do Sul, Goiás, Paraná, Santa Catarina and Rio Grande do Sul); by mesoregion for the states adjacent to these regions (i.e., Rondônia, Amazonas, Pará, Tocantins, Bahia, Minas Gerais, and São Paulo), and by state for the remaining states that are not adjacent to the Center-West and South regions (i.e., Acre, Roraima, Amapá, Maranhão, Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe, Espírito Santo, and Rio de Janeiro) (IBGE, 2021). The centroid of each microregion, mesoregion, or state is the virtual geographic center of the municipality with the highest volume, by product and by type (production or consumption).

Lastly, to reduce the number of origins o and destinations d due to computational limitations, the volume of the regions with low volume were allocated in the regions with higher volume, within the same microregion, mesoregion or state. The number of origins and destinations is 106 and 96 for maize, 102 and 69 for soybean, and 69 and 96 for soybean meal, respectively.

The 2035 values were estimated by total volume and then by state, using the 2020 values and the average annual growth rate of the last two years (MAPA, 2022).

exp_{pem} and imp_{pim} : The exported and imported monthly volumes were obtained using the waterway, maritime, road, and non-declared modes, and the following 6-digit Harmonized System (HS)¹⁶ codes: 100590 (maize), 120190 (soybean), and 230400 (soybean meal) (MDIC, 2023). The export demand is represented by the exporting port and the importing origin is characterized by the importing port or by the city of entry for road mode. There are 10 exporting ports and 7 entry points for maize, 14 exporting ports and 7 entry points for soybean, and 9 exporting ports for soybean meal.

The 2035 export values were estimated by total volume, using the 2020 values and the average annual growth rate of the last two years (MAPA, 2022). The 2035 import values were adjusted to enable a feasible solution for the problem.

isv_{pj} and msc_j : Maize, soybean, and soybean meal are stored in solid bulk warehouses. The warehouses were grouped by municipality and then by microregion, mesoregion, and state (CONAB, 2022b; IBGE, 2021), using the same grouping applied for sup_{pom} and dem_{pdm} . The centroid is the municipality with the highest static capacity. Afterwards, the total static capacity was adjusted by the annual growth rate (CONAB, 2022b) and by the participation of maize, soybean, and other grains in the total stored volume (IBGE, 2023). Lastly, to reduce the number of warehouses j due to computational limitations, the capacities of the warehouses with low volume were allocated in the regions with higher volume, within the same microregion, mesoregion or state, resulting in 153 solid bulk warehouses.

The initial volume stored per product per warehouse was estimated by state for maize and for the whole country for soybean and soybean meal (ABIOVE, 2023; Safras&Mercado, 2022a). Then, it was proportionally allocated to each warehouse.

¹⁶ The “Harmonized Commodity Description and Coding System”, known as "HS Nomenclature", is used by over 200 administrations worldwide to establish their national customs tariff and to gather economic statistical data. It includes around 5,000 commodity groups, that are identified by a 6-digit code and are organized according to a legal and logical structure. Countries can add additional subdivisions to address their necessities (European Commission, 2023b).

The 2035 static capacity was estimated by total volume, using the 2020 values and the average annual growth rate of the last two years (CONAB, 2022b). The 2035 initial stored volume was calculated by applying the 2020 values and adjusting to enable a feasible solution for the problem.

The second level model's parameters are summarized in Table 18.

Table 18. Parameters of the Brazil's agricultural products logistic network improvement model.

Parameter(s)	Value(s)	Source(s)
$f_{podm}, f_{poem}, f_{poj}, f_{pjd}, f_{pjem},$ and f_{pidm} (road freight costs)	Estimated for each O-D pair using a linear regression of the 2017 and 2020 road freight cost (in R\$/tonne)	SIFRECA (ESALQ-LOG, 2022)
pro_{pom} and prj_{pjm} (price of products)	2017 and 2020 monthly values (in R\$/tonne)	Safras&Mercado (2022b); IBGE (2021)
pri_{pim} (price of imported products)	Calculated by dividing the imported value by the imported volume and multiplying by the monthly exchange rate in 2017 and 2020 (in R\$/tonne)	BACEN (2023); MDIC (2023)
txo_{pod}, txj_{pjd} and txi (taxes)	Between 0% and 8.4%, depending on the destination	ESALQ-LOG (2020); Guimarães (2022); Rezende (2022)
$em_{od}, em_{oe}, em_{oj}, em_{jd}, em_{je},$ and em_{id} (CO ₂ emission rate)	0.03914 kgCO ₂ /t.km for road mode, 0.01975 kgCO ₂ /t.km for railways, and 0.00790 kgCO ₂ /t.km for waterways and cabotage	Rocha (2020)
Distances	Calculated for each O-D pair by the Route solver (in km)	ArcGIS Pro (ESRI, 2023)
hd_j (storage handling and drying fee)	Between R\$25.00/tonne and R\$30.50/tonne, depending on the state	SIARMA (ESALQ-LOG, 2019, 2020)
ms_j (monthly storage fee)	Between R\$5.00/tonne and R\$6.00/tonne, depending on the state	SIARMA (ESALQ-LOG, 2019, 2020)
sup_{pom} (production volumes)	2017 and 2020 maize and soybean: annual production volumes were combined with the monthly harvest schedule by state; soybean meal: soybean annual crushing capacity adjusted by the annual volume; 2035 volumes were estimated (in tonnes)	IBGE (2022b, 2021); CONAB (2022a); SANCHES (2018); ABIOVE (2023); Ary Oleofar (2023); Safras&Mercado (2022a); MAPA (2022)

Parameter(s)	Value(s)	Source(s)
dem_{pdm} (consumption volumes)	2017 and 2020 soybean: soybean annual crushing capacity adjusted by the annual volume; maize and soybean meal: number of poultry and pigs per municipality, multiplied by the consumption of each animal and adjusted by the annual consumption volume; 2035 volumes were estimated (in tonnes)	ABIOVE (2023); Ary Oleofar (2023); Safras&Mercado (2022a); IBGE (2022c, 2021); Santos-Filho et al. (2018); ESALQ-LOG (2020); MAPA (2022)
exp_{pem} and imp_{pim} (exported and imported volumes)	2017 and 2020 volumes were obtained using HS-6 codes; 2035 volumes were estimated (in tonnes)	MDIC (2023); MAPA (2022)
msc_j (maximum storage capacity)	Warehouses were grouped, then the total static capacity was adjusted by the annual growth rate and by the participation of maize, soybean, and other grains in the total stored volume (in tonnes)	CONAB (2022b); IBGE (2023, 2021)
isv_{pj} (initial stored volume)	Estimated by state for maize and for the whole country for soybean and soybean meal, then was proportionally allocated to each warehouse (in tonnes)	CONAB (2022b); IBGE (2021); ABIOVE (2023); Safras&Mercado (2022a)

5. RESULTS AND DISCUSSION

Chapter 5 presents the computational experiments, results, and discussion for the first level (section 5.1) and the second level (section 5.2) models. Afterwards, the modal split of the improved Brazilian transportation network is compared with other countries of comparable size in section 5.3.

5.1. Railway network design model

The objective of the first level model is to design a new railway, selecting both links and terminals, that maximize the benefit-cost ratio. The transshipment operations entail increases of time and loss; thus, the attractiveness of a railway mainly depends on the terminals' proximity to production and consumption areas, as the reduction in the total transport cost (sum of pre-haul, long-haul, and end-haul) must compensate the lesser level of service. On the other hand, it is economically unfeasible to open a terminal in every municipality. Hence, this thesis tested four options of terminal location criterion in section 5.1.1 and assessed which one delivered the best performance.

Afterwards, section 5.1.2 presents the seven scenarios that tested criteria to define the area of influence and potential cargo, concluding the calibration of the railway network design model.

5.1.1. Scenarios 1 to 4 – best location of new terminals

In scenarios 1 to 4, four options of grouping municipalities by volume are tested to determine the best location of the new possible railway terminals: the virtual geographic center of the immediate geographic region's municipality with the highest flow volume (scenario 1), the immediate geographic region weighted mean center by total flow volume (scenario 2), the virtual geographic center of the microregion's municipality with the highest flow volume (scenario 3), and the microregion weighted mean center by total flow volume (scenario 4).

Links that directly connected two states but missed a state in between were removed. For instance, links connecting Paraná and Rio Grande do Sul states were deleted as they overlooked the Santa Catarina state.

In scenario 1, there are 148 new possible terminals and 412 new possible links (shown in Figure 16). The constructive heuristic generated 41 different solutions out of 86 iterations in a total running time of 4 hours and 51 minutes.

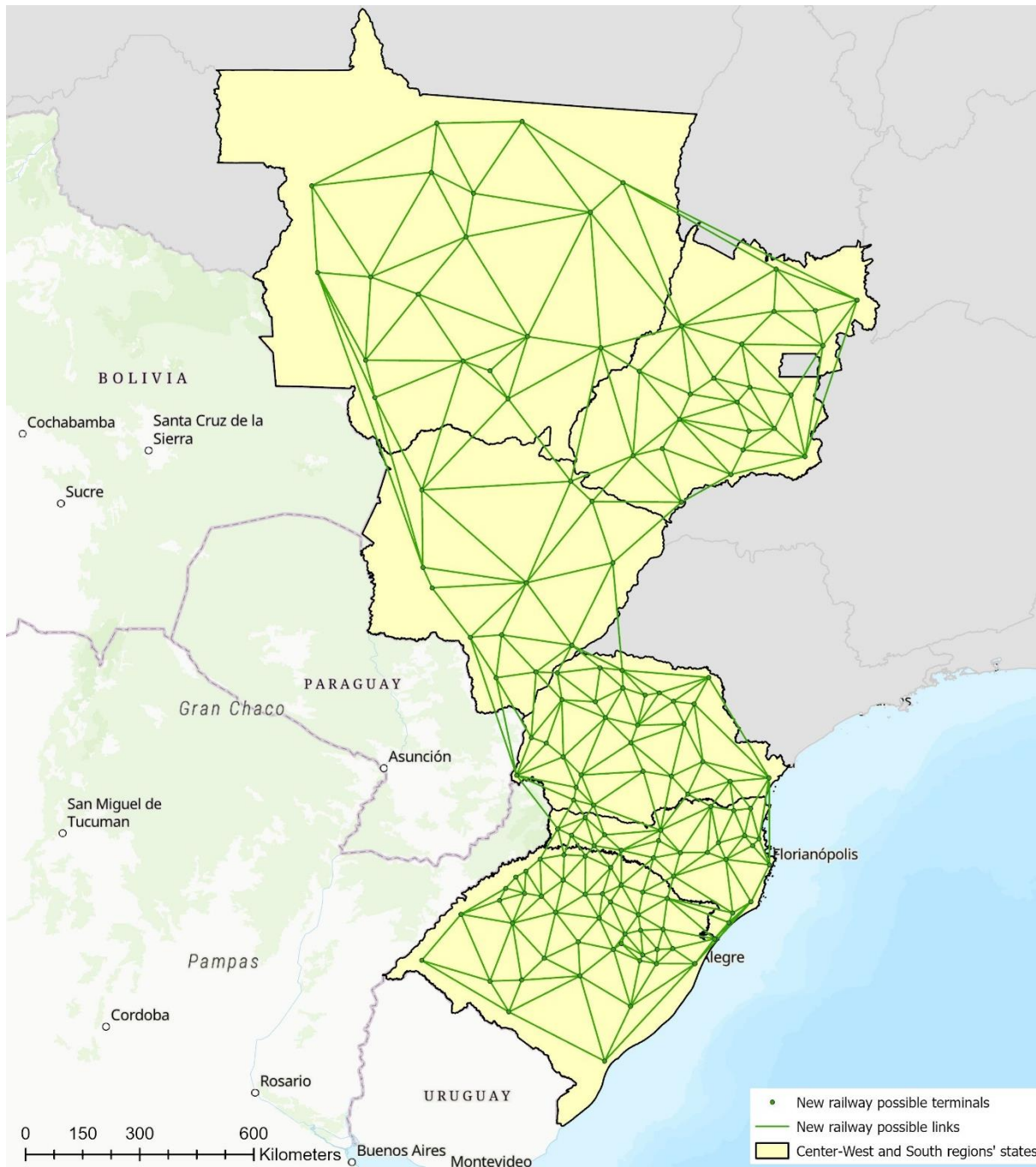


Figure 16. New railway possible links and terminals – scenario 1.

The best solution has a benefit-cost ratio of 0.03126, 7 links with a total extension of 1,232 km, and 6 terminals (Diamantino (MT), Cuiabá (MT), Rondonópolis (MT), Costa Rica (MS), Chapadão do Sul (MS) and Lobato (PR)). It is shown in Figure 17.

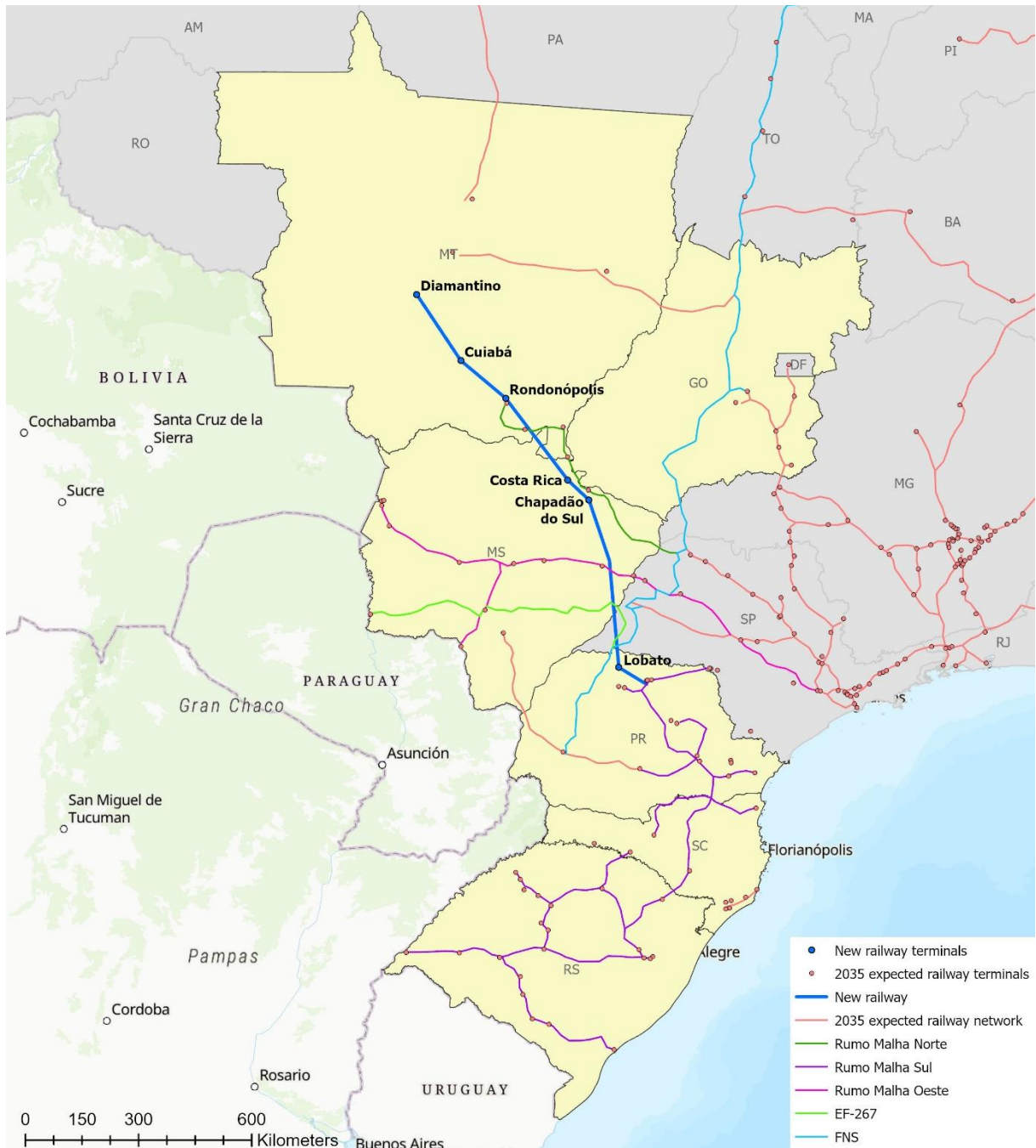


Figure 17. Best solution – scenario 1.

A terminal is only opened when there is either cargo accessing or exiting the railway. Cargo can also change to another railway when there is an intersection and can either access or exit the railway network through a terminal from the 2035 expected railway network.

The scenario 1 best solution runs near the Rumo Malha Norte railway between Rondonópolis (MT) and Chapadão do Sul (MS) and ends in the Rumo Malha Sul railway, near the terminals of Londrina (PR), Cambé (PR) and Rolândia (PR). The new railway intersects with Rumo

Malha Oeste railway near the Rio Branco (MS) terminal, with the EF-267 (Pantanal Railway) at Brasilândia (MS) and Mirante do Paranapanema (SP) municipalities, and with the FNS also at Mirante do Paranapanema (SP). Figure 18 illustrates a closer look of the best solution.

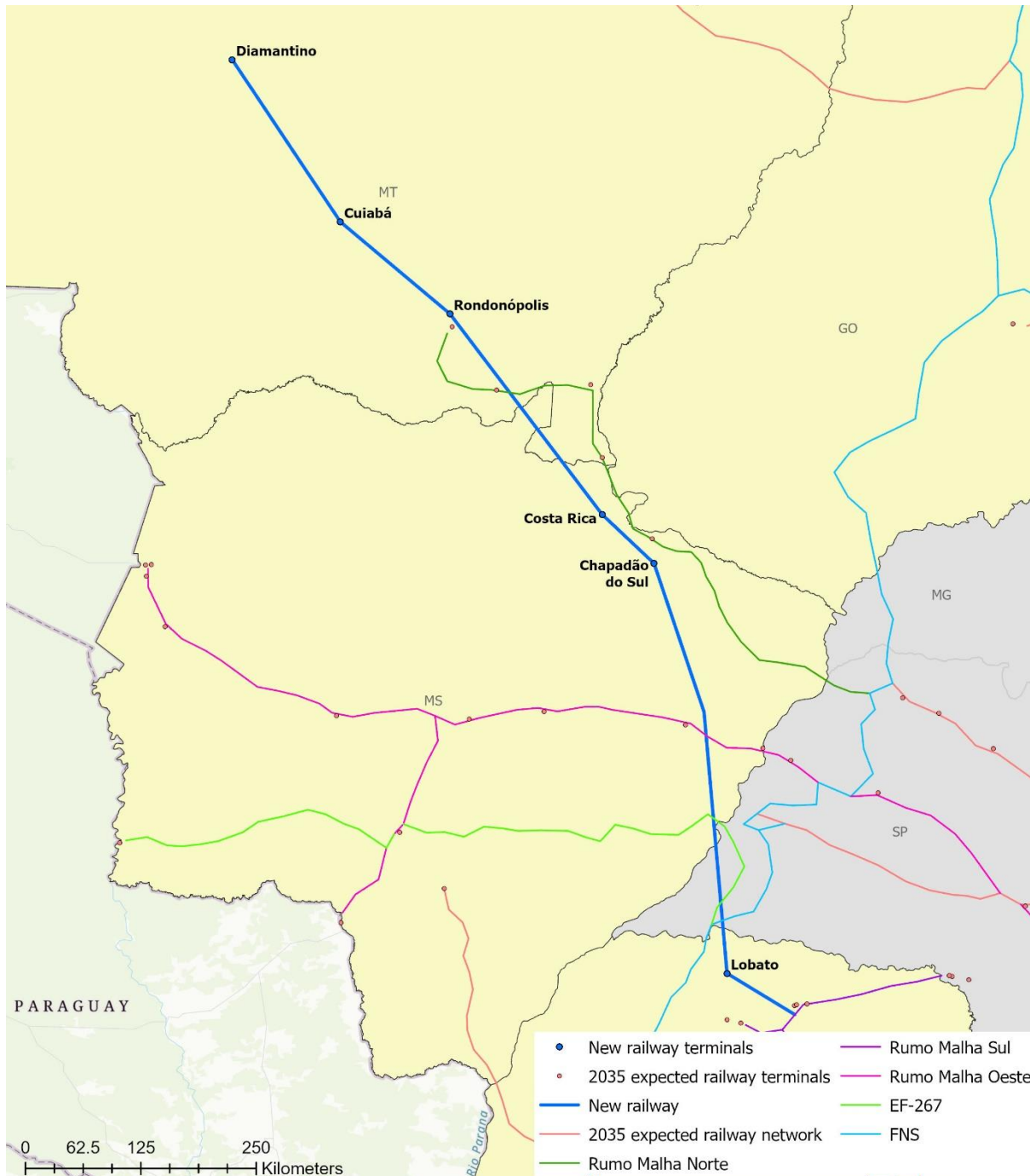


Figure 18. Zoom of the best solution – scenario 1.

In scenario 2, there are also 148 new possible terminals and 412 new possible links (shown in Figure 19). The constructive heuristic generated 35 different solutions out of 80 iterations in a total running time of 4 hours and 22 minutes.

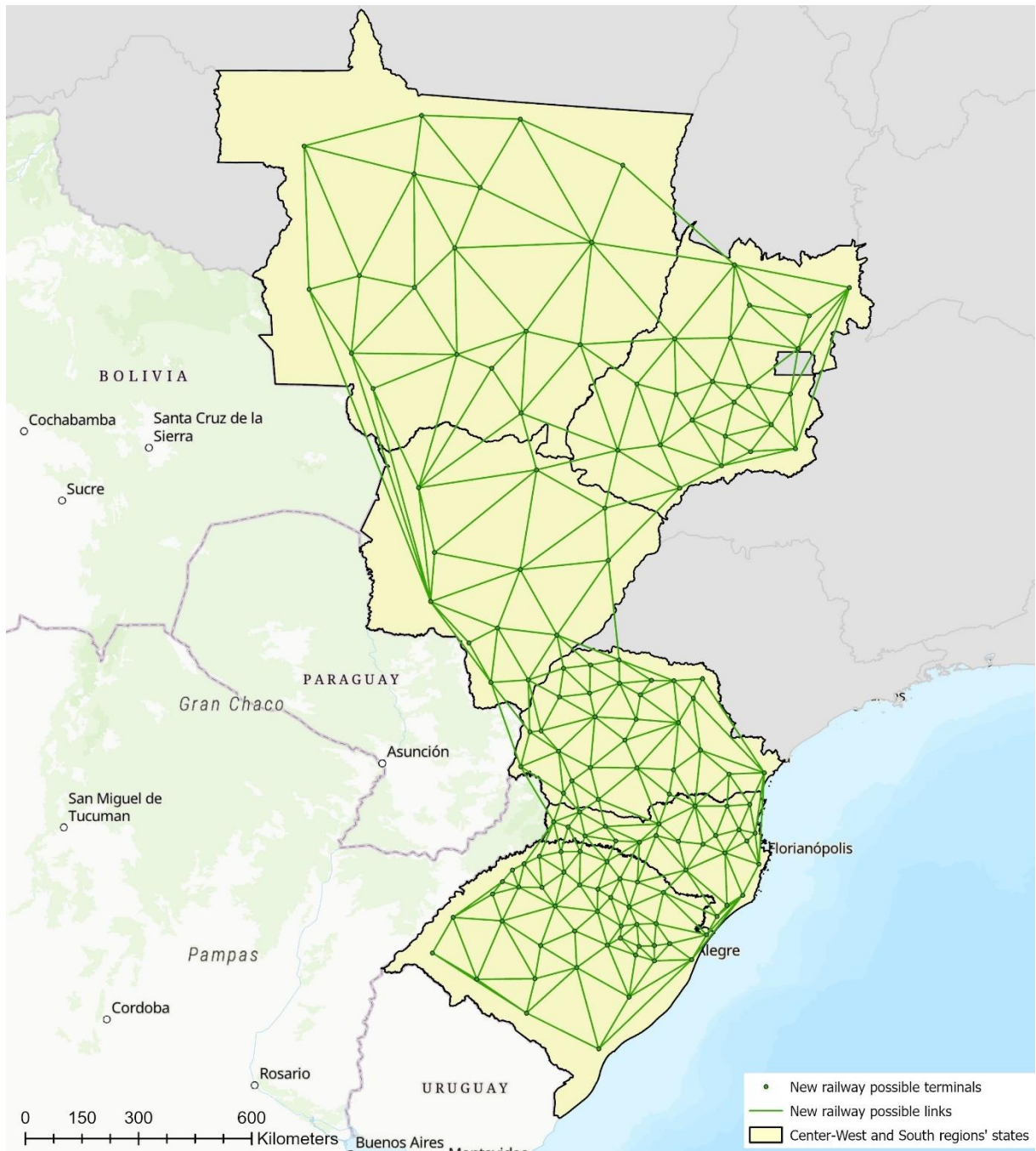


Figure 19. New railway possible links and terminals – scenario 2.

The best solution (Figure 20) has a benefit-cost ratio of 0.01772, 11 links with a total extension of 1,381 km and 4 terminals (Jaciara (MT), Maringá (PR), Apucarana (PR) and Telémaco Borba (PR)).

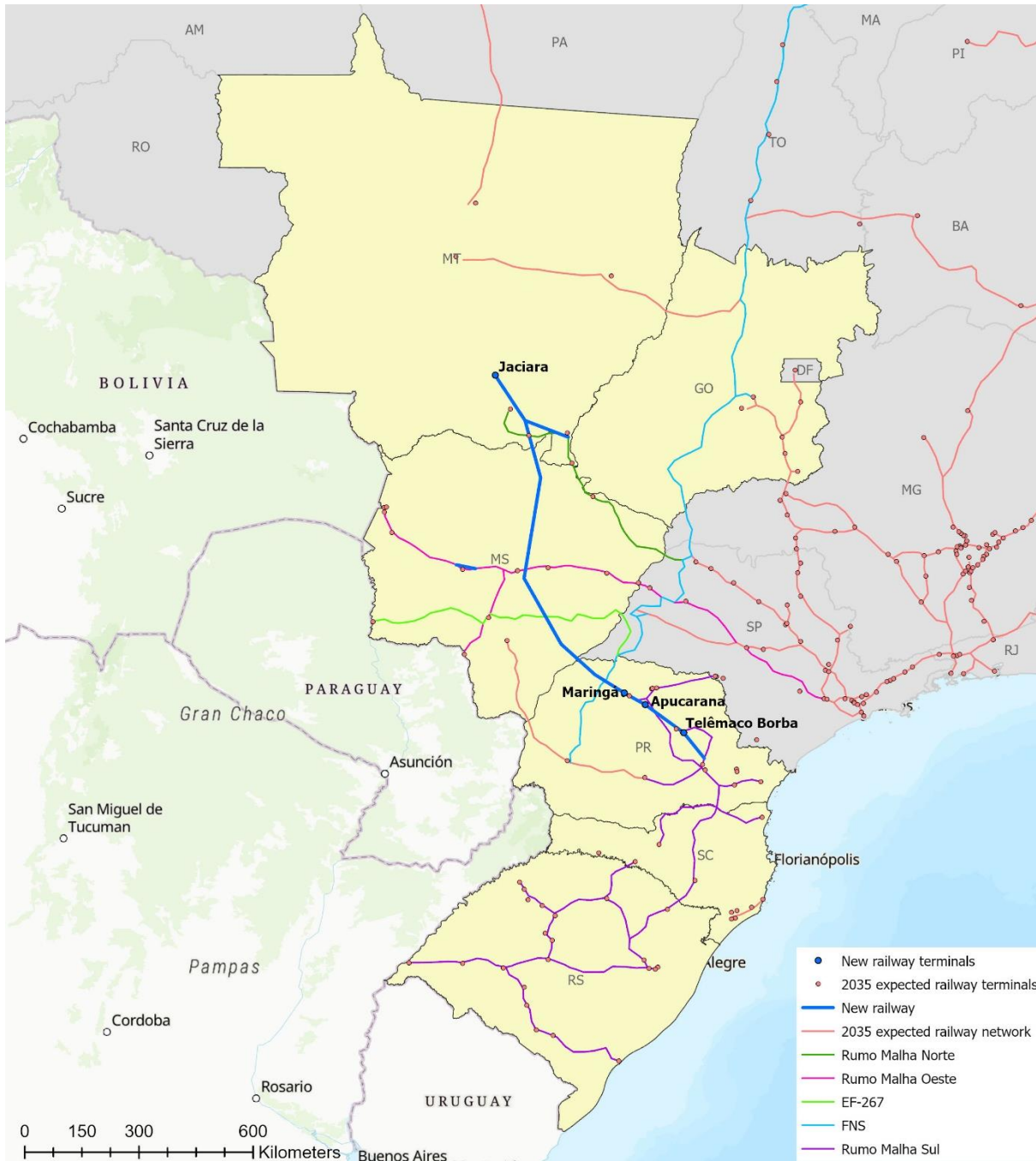


Figure 20. Best solution – scenario 2.

The scenario 2 best solution has a branch from Pedra Preta (MT) to Alto Araguaia (MT), where the new railway intersects with the Rumo Malha Norte railway. The solution also intersects with the Rumo Malha Norte at the Itiquira (MT) terminal, with the Rumo Malha Oeste railway near the Campo Grande (MS) terminal, with the EF-267 (Pantanal Railway) at the Nova Alvorada do Sul (MS) municipality, and with the FNS at Paranavaí (PR). From Maringá (PR) and Sarandi (PR) onwards, the new railway goes along, intersects, and ends at the Rumo Malha Sul railway in the Carambeí (PR) municipality near the terminal of Ponta Grossa (PR). There is also a small

branch in the Aquidauana (MS), municipality which practically overlaps with the Rumo Malha Oeste railway. Figure 21 illustrates a zoom of the scenario 2 best solution.

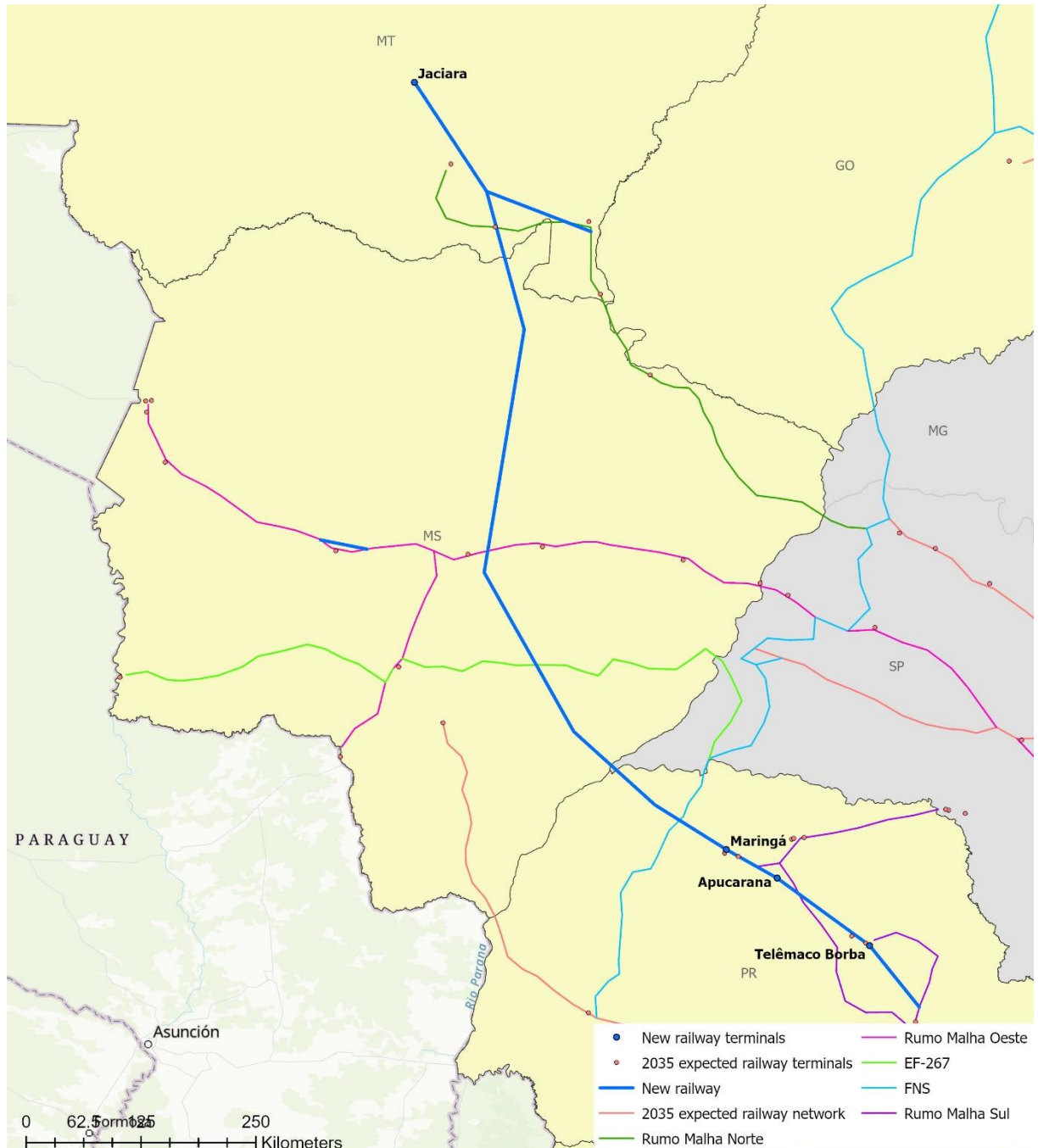


Figure 21. Zoom of the best solution – scenario 2.

In scenario 3, there are 145 new possible terminals and 404 new possible links (shown in Figure 22). The constructive heuristic generated 34 different solutions out of 79 iterations in a total running time of 4 hours and 24 minutes.

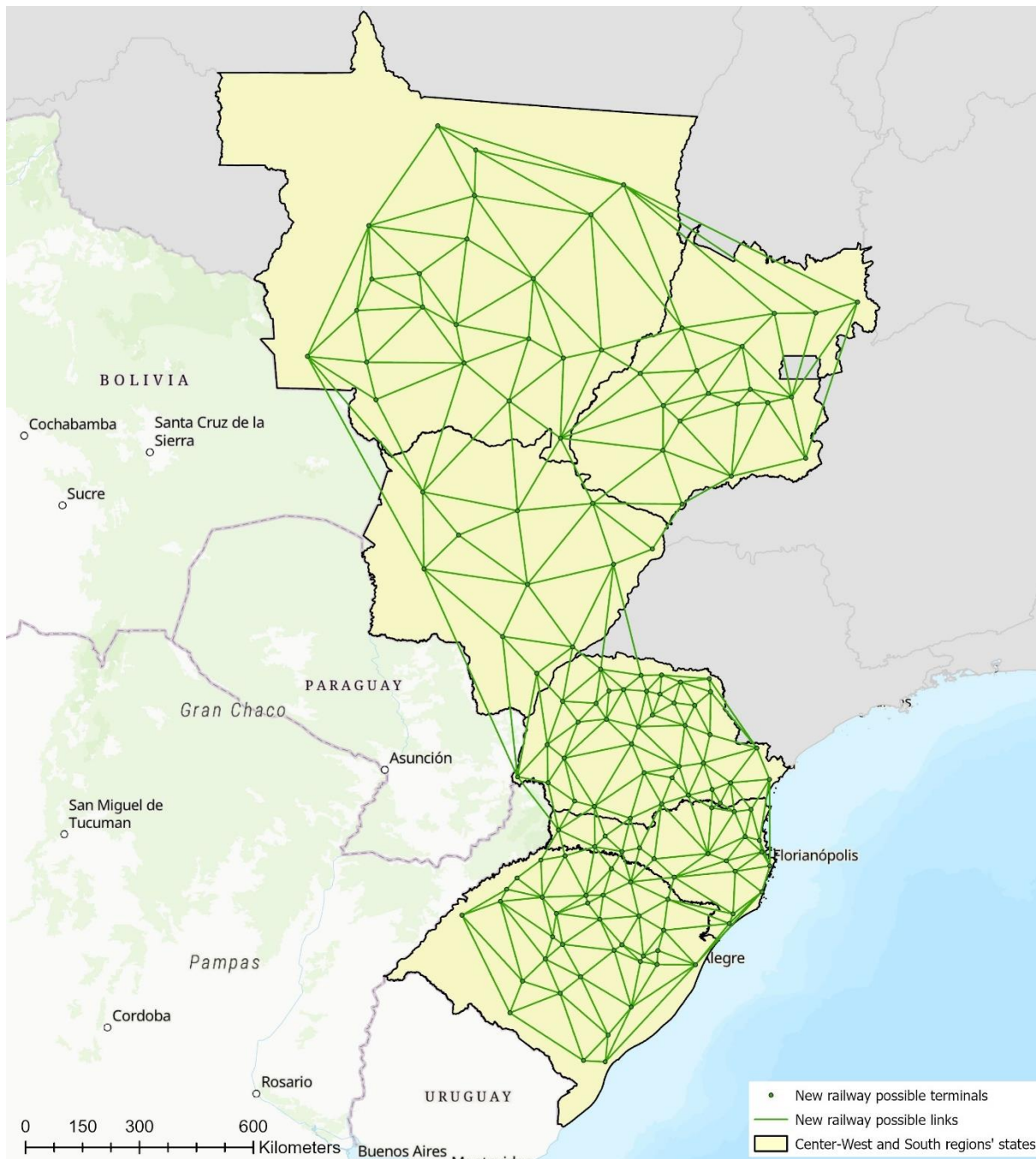


Figure 22. New railway possible links and terminals – scenario 3.

The scenario 3 best solution has a benefit-cost ratio of 0.03486, 9 links with a total extension of 1,291 km, and 6 terminals (Rosário Oeste (MT), Cuiabá (MT), Rondonópolis (MT), Chapadão do Sul (MS), Jaguapitã (PR) and Arapongas (PR)). It is shown in Figure 23.

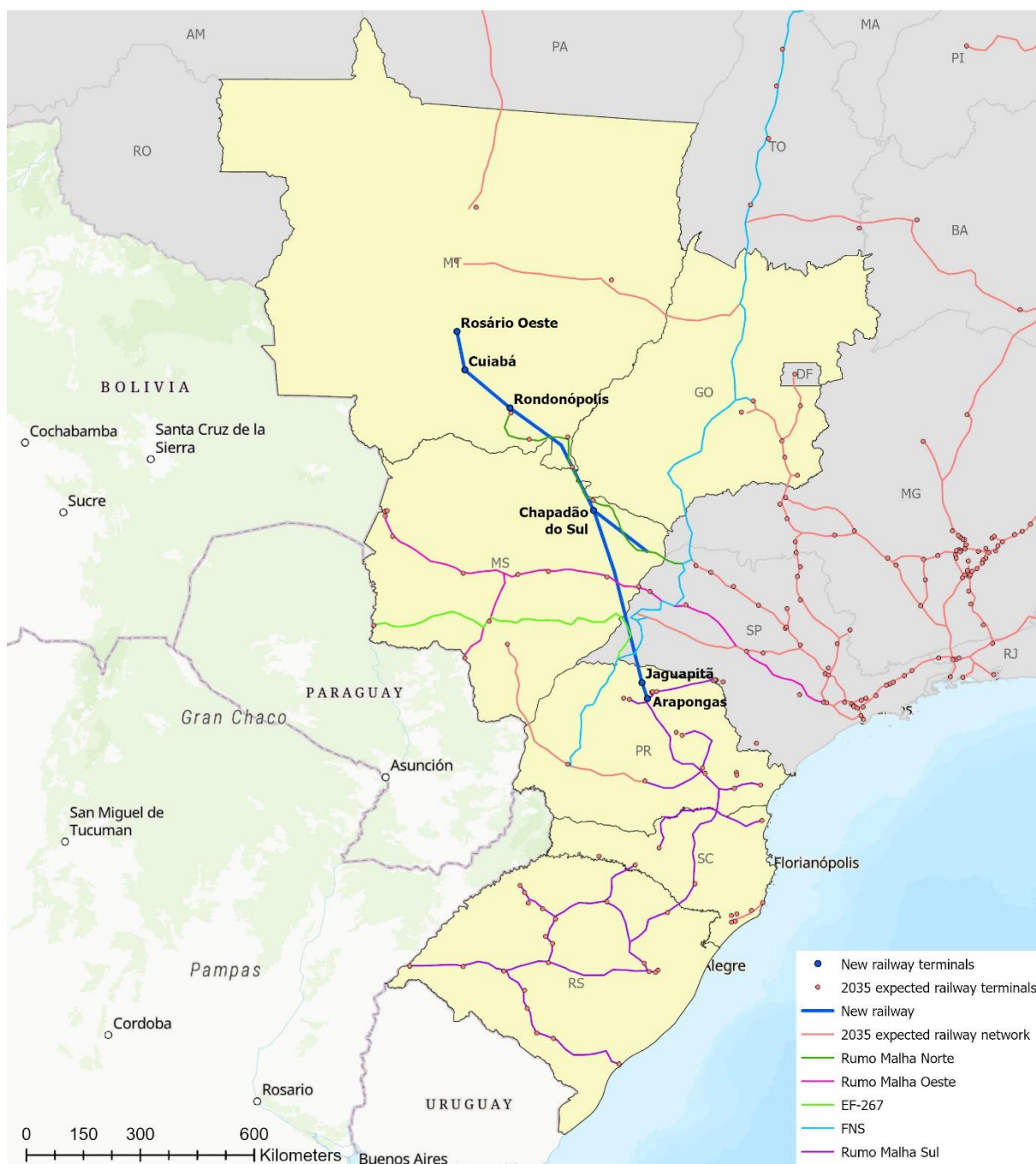


Figure 23. Best solution – scenario 3.

The new railway runs near the Rumo Malha Norte railway between Rondonópolis (MT) and Chapadão do Sul (MS) and has a branch between Chapadão do Sul and Aparecida do Taboado (MS) that practically overlaps with the Rumo Malha Norte. The scenario 3 best solution intersects with Rumo Malha Oeste railway near the Rio Branco (MS) terminal, overlaps with the EF-267 (Pantanal Railway) at Presidente Venceslau (SP) municipality, and intersects with the FNS at

Sandovalina (SP). It ends in the Rumo Malha Sul railway in the Arapongas (PR) municipality near the terminals of Cambé (PR) and Rolândia (PR). Figure 24 illustrates a closer look at the best solution.

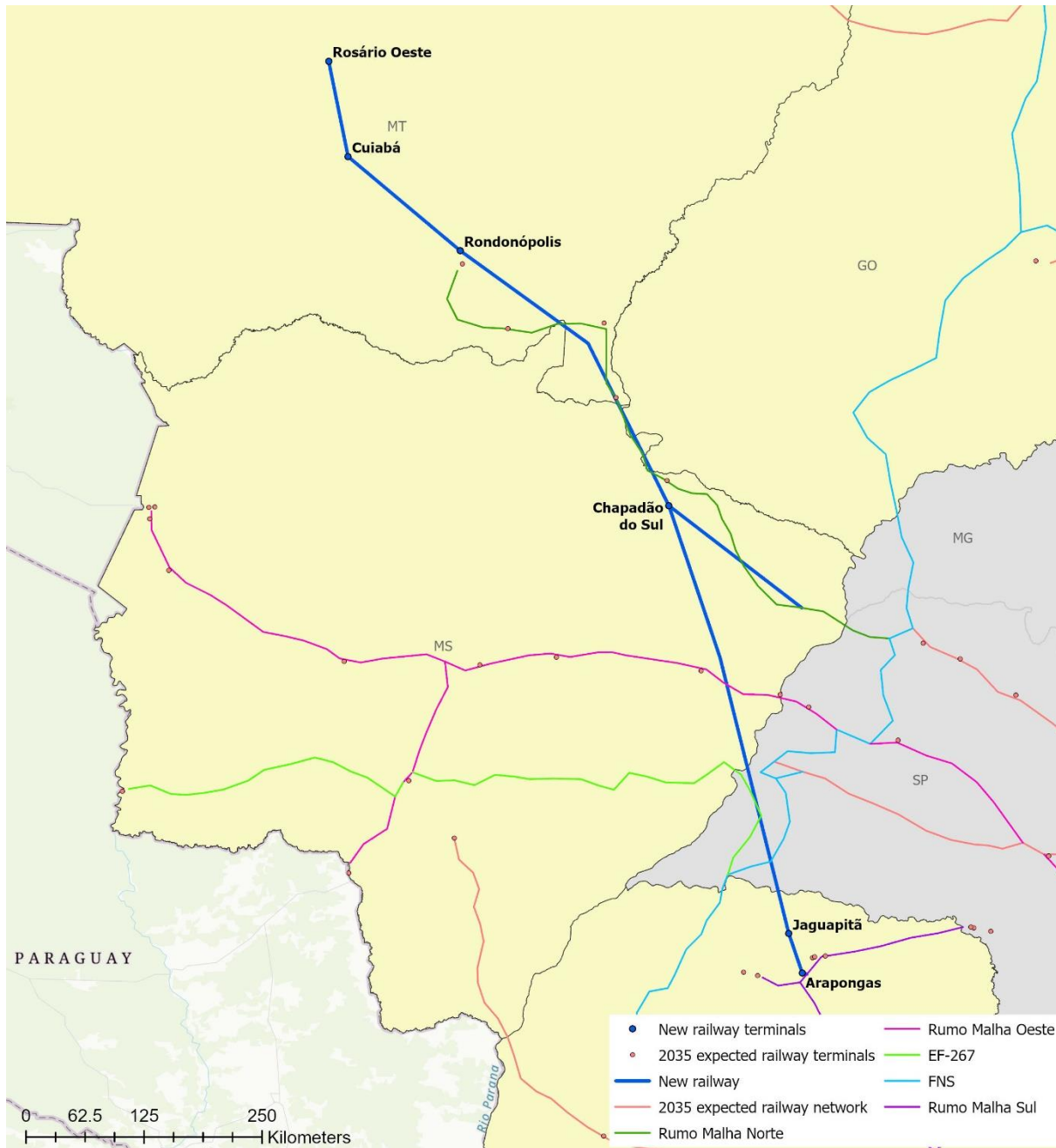


Figure 24. Zoom of the best solution – scenario 3.

In scenario 4, there are 145 new possible terminals and 406 new possible links (shown in Figure 25). The constructive heuristic generated 38 different solutions out of 83 iterations in a total running time of 4 hours and 20 minutes.

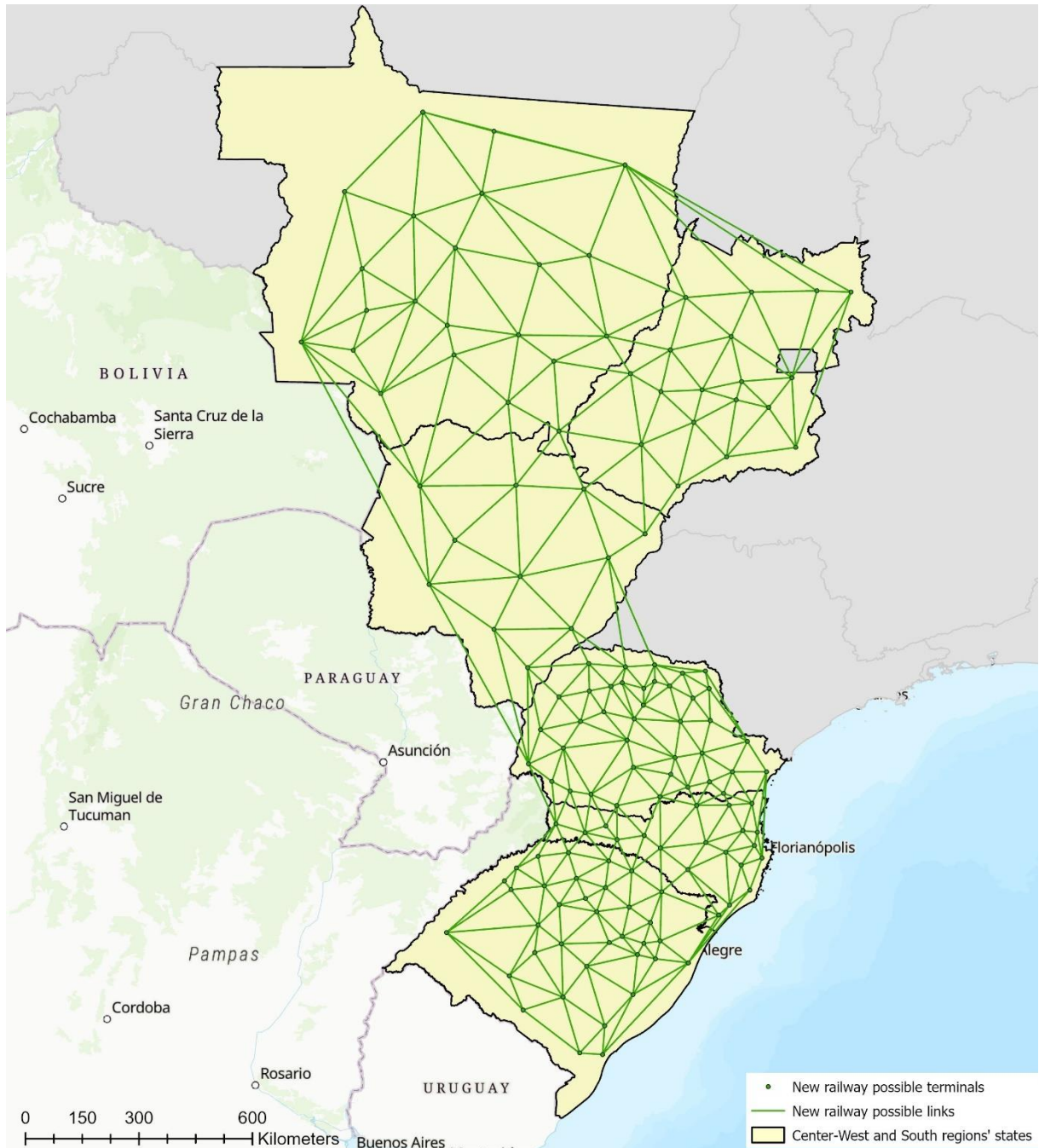


Figure 25. New railway possible links and terminals – cenário 4.

The best solution (Figure 26) has a benefit-cost ratio of 0.02331, 8 links with a total extension of 1,202 km and 7 terminals (Rosário Oeste (MT), Cuiabá (MT), Rondonópolis (MT), Alto Araguaia (MT), Chapadão do Sul (MS), Bela Vista do Paraíso (PR) and Joinville (SC)).



Figure 26. Best solution – scenario 4.

The scenario 4 best solution intersects with the Rumo Malha Norte at the Rondonópolis (MT) terminal and practically overlaps with it from Alto Araguaia (MT) to Chapadão do Sul (MS). The new railway intersects with the Rumo Malha Oeste railway near the Rio Branco (MS) terminal and with the FNS at the municipalities of Ouro Verde (SP) and Presidente Bernardes (SP), ending at the Rumo Malha Sul railway in Ibiporã (PR), close to the terminal of Londrina (PR). There is also a branch starting at the Rumo Malha Sul railway in Curitiba (PR), near the terminal of Araucária

(PR), and ending at the new terminal of Joinville (SC). Figure 27 shows a zoom of the scenario 4 best solution.

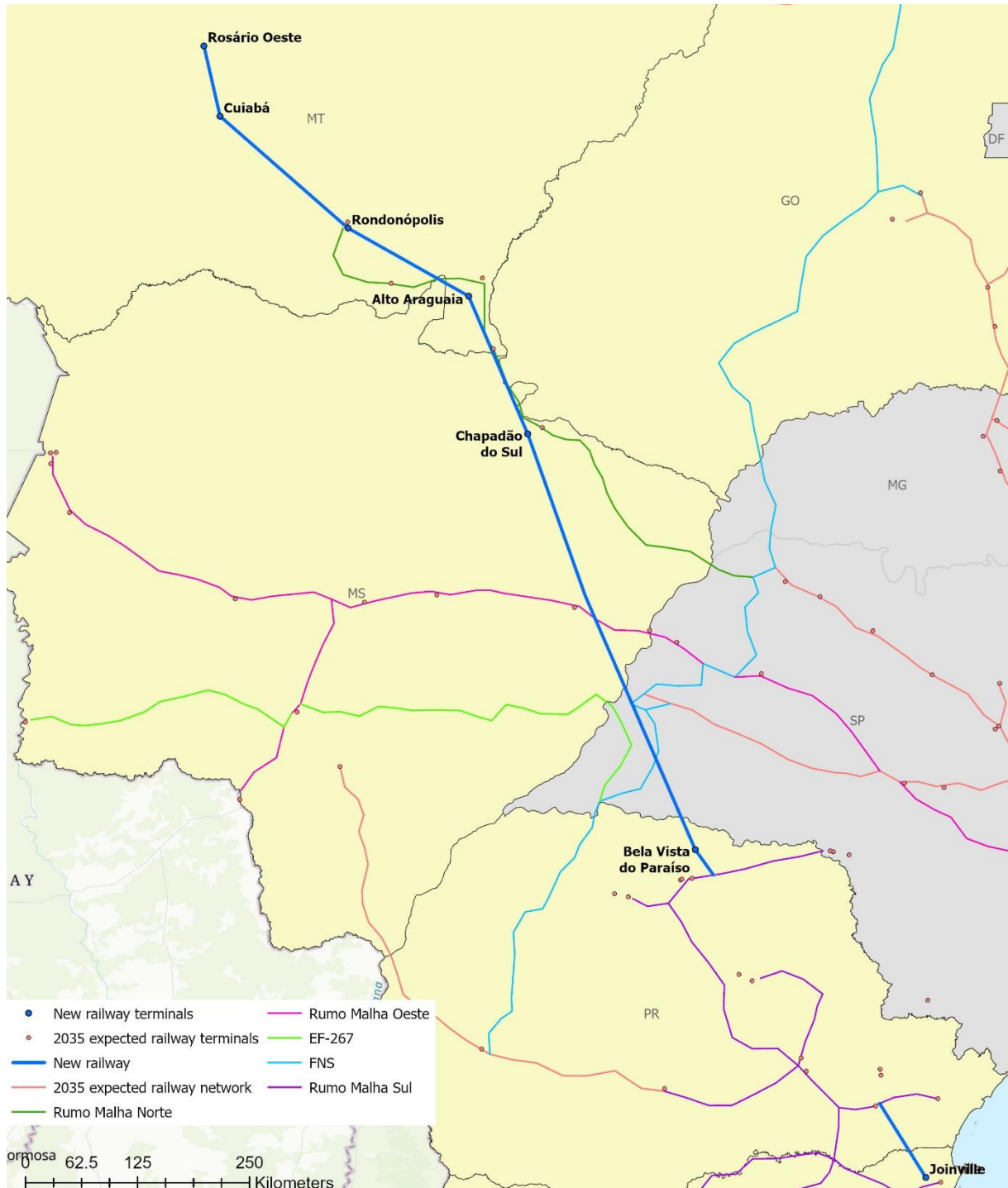


Figure 27. Zoom of the best solution – scenario 4.

The scenarios 1 to 4 best solutions' data are summarized in Table 19. Scenario 3, with the new terminals located at the virtual geographic center of the microregion's municipality with the highest flow volume, has the best solution overall. It has the highest benefit-cost ratio (0.03486),

the highest reduction in transportation cost (R\$ 1.14 billion), and the highest maximum transported volume per link (57.93 million tonnes, in the stretch between Alto Taquari (MT) and Chapadão do Sul (MS)). The participation in the Brazilian domestic transportation matrix (5.42% of total TKU) is very similar to the highest value from scenario 1.

Table 19. Railway network design model - results of scenarios 1 to 4.

	Scenario 1: Immediate geographic region's municipality with the highest flow volume	Scenario 2: Immediate geographic region weighted mean center by total flow volume	Scenario 3: Microregion's municipality with the highest flow volume	Scenario 4: Microregion weighted mean center by total flow volume
Solution value - Benefit-cost ratio	0.03126	0.01772	0.03486	0.03438
Extension (km)	1,232	1,381	1,291	1,202
Number of links	7	11	9	8
Number of terminals	6	4	6	7
Reduction in transportation cost (million R\$)	977.23	619.16	1,141.24	1,049.78
%TKU (domestic routes)	5.46%	5.31%	5.42%	5.21%
Links maximum transported volume (domestic routes) (t)	54,774,595	45,376,393	57,929,585	55,363,905
Links minimum transported volume (domestic routes) (t)	13,665,866	7,012,246	12,568,175	13,539,215
Terminals maximum transported volume (t)	35,291,925	32,766,786	35,101,966	36,795,035
Terminals minimum transported volume (t)	61,709	254,540	246,447	111,261
Traversed states	MT, MS, and PR	MT, MS, and PR	MT, MS, and PR	MT, MS, PR, and SC

Scenarios 1 and 3, with terminals located at the geographic center of the municipality with the highest flow volume, generated better results than scenarios 2 and 4, where terminals are at the weighted mean center by total flow volume. It occurred because the new terminals are located very close to the main flow and freight generators in scenarios 1 and 3, reducing the total freight cost and increasing the new railway appeal.

The best solution of scenario 4, with the new terminals placed at the microregion weighted mean center by total flow volume, comes in a close second place. Its design is very similar to scenario 3, except for the branches: in scenario 3, there is a branch starting at the new terminal of Chapadão do Sul (MS) and ending at the Rumo Malha Norte railway in Aparecida do Taboado

(MS); while in scenario 4, a branch starts at the Rumo Malha Sul railway in Curitiba (PR) and ends at the new terminal of Joinville (SC). It can be said that the scenario 4 design is better than scenario 3's, since the latter's branch practically overlaps with the Rumo Malha Norte, whilst the former's branch adds a new connection to the railway network between the states of Paraná and Santa Catarina.

Scenario 4 was the only one with a new link and a new terminal in the state of Santa Catarina and it is not even connected to the main new railway. This poor result for the states of Santa Catarina and Rio Grande do Sul is due to the O-D cargo matrix since the volume between these states and Paraná and the Center-West region sums up to only 26.9 million tonnes (distributed among 140 O-D pairs) and 31.7 million tonnes (67 O-D pairs), respectively.

Although the microregion and mesoregion classifications were created in 1989 and the immediate and intermediary geographic region categorization was released in 2017 as an updated concept (IBGE, 2018), the scenarios 1 to 4 results showed that the older classification still provides a better grouping. Such that recent studies continue to use the microregion and mesoregion division instead of the newer one (Branco et al., 2020; Isler et al., 2021; João, 2021; Péra, 2022; Plaza et al., 2020).

Thus, the railway network design model will use the virtual geographic center of the microregion's municipality with the highest flow volume to locate the new terminals.

It is important to highlight that the solution obtained depends on the expected 2035 multimodal infrastructure. For instance, most of the railway network in Rio Grande do Sul is currently inactive, in need of maintenance or with a different gauge than other railways. If the railway network is not actually available for use, the solutions would probably select links and terminals in this state. Furthermore, the expected 2035 railway network only considered the Nova Ferroeste stretch between Dourados (MS) and Cascavel (PR), overlooking the stretches from Maracaju (MS) to Dourados, Guarapuava (PR) to port of Paranaguá (PR), Cascavel to Foz do Iguaçu (PR), and Cascavel to Chapecó (SC). The complete Nova Ferroeste is a strong competitor to the new railway since it links the same states, so its addition to the railway network would lead to a different solution.

5.1.2. Scenarios 5 to 10 – best area of influence and potential cargo

In scenarios 5 to 10, six options are tested to determine the best criteria to define the area of influence and potential cargo: Center-West and South regions and its neighboring states cargo matrix total volume (scenario 5) and only agricultural bulk solids (scenario 6), Center-West and

South regions and its neighboring mesoregions cargo matrix total volume (scenario 7) and only agricultural bulk solids (scenario 8), and Center-West and South regions and its neighboring microregions cargo matrix total volume (scenario 9) and only agricultural bulk solids (scenario 10). These six options reflect the criteria commonly used in railway design projects in real world (EDLP, 2022, 2016c; TPF-SENER, 2022a, 2022b; VALEC, 2015) and will be compared to the results obtained with the Brazilian O-D cargo matrix total volume (scenario 3). The idea is to evaluate if a more extensive area of influence and/or portfolio of products generates different results and leads to different decision making. Table 20 summarizes these scenarios' best solution data.

The O-D pairs for scenarios 5 to 10 were generated by applying filters in the Brazilian O-D cargo matrix used in scenarios 1 to 4, which was detailed in section 4.2.2. The location filter considered the regions of interest as either Origin or Destination, thus there are O-D pairs where the complementary locality is from outside the selected territories, e.g., Rio Grande (RS)-Europe. As the number of O-D pairs with agricultural bulk solids is considerably lower than the number with all cargo groups, the minimum annual volume is lowered to 10,000 tonnes for Origins or Destinations from the Center-West and South regions and 40,000 tonnes for the remaining O-D pairs in scenarios 6, 8, and 10.

Scenarios 5, 7 and 9 generated the same best solution than scenario 3 (as already seen on Figures 23 and 24), although scenarios 7 and 9 presented slightly lower values for the benefit-cost ratio (0.03486 vs. 0.03463), reduction in transportation cost (R\$ 1.14 billion vs. R\$ 1.13 billion), and maximum transported volume per link (57.93 million tonnes vs. 56.99 million tonnes, in the stretch between Alto Taquari (MT) and Chapadão do Sul (MS)). This small difference is due to the exclusion of the O-D pair Porto Velho (RO) – São Paulo (SP) from the scenarios 7 and 9. The participation in the Brazilian domestic transportation matrix increased in all three scenarios, since only a part of the Brazilian O-D cargo matrix was considered.

Hence, the best option to define a railway's area of influence involves the states that the new railway is going to traverse and its neighboring states (scenario 5). This criterion finds exactly the same solution as when the whole Brazilian O-D matrix is used, while saving data volume and processing time.

Scenarios 6, 8, and 10 found exactly the same best solution, which is equivalent to a stretch of 567 km of scenarios 3, 5, 7, and 9 best solutions, between Rosário Oeste (MT) and Chapadão do Sul (MS). Figure 28 shows a zoom of the best solution for scenarios 6, 8 and 10.

Table 20. Railway network design model - results of scenarios 3 and 5 to 10.

	Scenario 3: Brazilian O-D cargo matrix total volume	Scenario 5: Center-West and South regions and its neighboring states cargo matrix total volume	Scenario 6: Center-West and South regions and its neighboring states only agricultural bulk solids	Scenario 7: Center-West and South regions and its neighboring mesoregions cargo matrix total volume	Scenario 8: Center-West and South regions and its neighboring mesoregions only agricultural bulk solids	Scenario 9: Center-West and South regions and its neighboring microregions cargo matrix total volume	Scenario 10: Center-West and South regions and its neighboring microregions only agricultural bulk solids
Solution value - Benefit-cost ratio	0.03486	0.03486	0.01602	0.03463	0.01602	0.03463	0.01602
Extension (km)	1,291	1,291	567	1,291	567	1,291	567
Number of links	9	9	4	9	4	9	4
Number of terminals	6	6	3	6	3	6	3
Reduction in transportation cost (R\$ million)	1,141.24	1,141.24	230.63	1,133.68	230.63	1,133.68	230.63
%TKU (domestic routes)	5.42%	5.73%	3.14%	9.41%	3.30%	10.42%	3.32%
Links maximum transported volume (domestic routes) (t)	57,929,585	57,929,585	9,761,128	56,993,771	9,761,128	56,993,771	9,761,128
Links minimum transported volume (domestic routes) (t)	12,568,175	12,568,175	8,804,710	11,632,361	8,804,710	11,632,361	8,804,710
Terminals maximum transported volume (t)	35,101,966	35,101,966	26,423,044	35,101,966	26,423,044	35,101,966	26,423,044
Terminals minimum transported volume (t)	246,447	246,447	2,801,635	246,447	2,801,635	246,447	2,801,635
Traversed states	MT, MS, and PR	MT, MS, and PR	MT and MS	MT, MS, and PR	MT and MS	MT, MS, and PR	MT and MS
Number of O-D pairs	3,498	3,351	2,895	3,050	2,814	2,986	2,782
Total running time (hours)	4:24	5:55	3:23	4:02	4:20	3:24	4:09

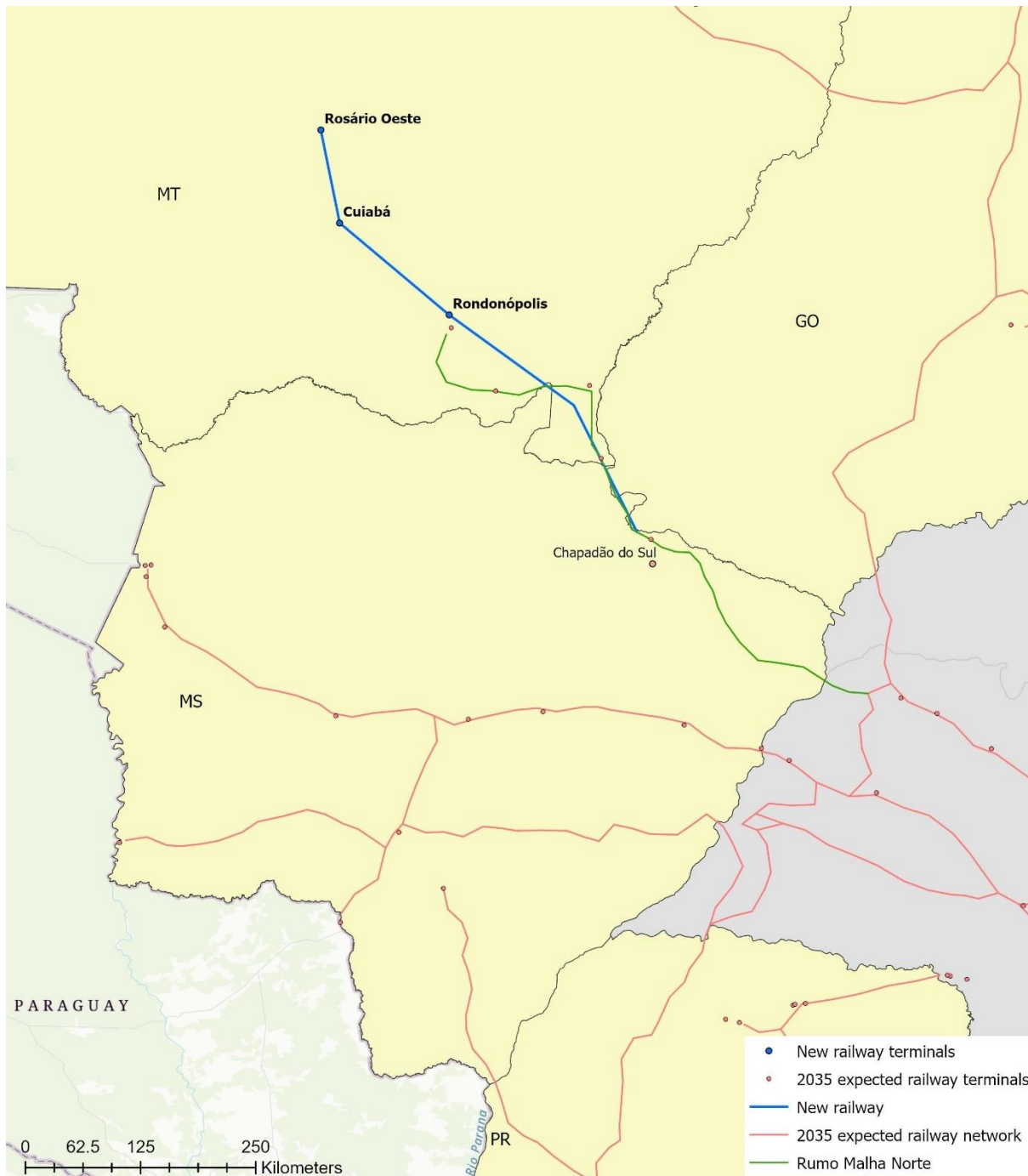


Figure 28. Zoom of the best solution – scenarios 6, 8 and 10.

The scenarios 6, 8, and 10 best solution's indicators were considerably lower than that of scenarios 3, 5, 7, and 9. Thus, it is possible to conclude that choosing only a set of products, even if they are the most significant for their regions, can lead to a much lower estimate of the potential cargo for a new railway and can result in a different railway design.

Finally, the railway network design model will use the virtual geographic center of the microregion's municipality with the highest flow volume to locate the new terminals; the states that

the new railway is going to traverse and its neighboring states as the area of influence; and the total volume as the potential cargo.

5.2. Brazil's agricultural products logistic network improvement model

The objective of the second level model is to optimize the Brazilian agricultural products logistic network, by finding the O-D flows and storage volumes that minimize the total logistic cost and CO₂ emissions. As the supply and demand volumes are given and each O-D pair has a minimum cost route that can be either by road or multimodal, the optimal solution finds the set of transportation infrastructures - especially the new railway proposed by the first level model - and warehouses that minimize the objective function.

Thus, several scenarios were built to evaluate the impact of new or improved logistic infrastructures. The first four scenarios (section 5.2.1) used 2017 data and networks to validate the linear programming model. This year was chosen as it is also the validation year for the PNL-2035.

The following scenarios were set on 2035 and focused on assessing the impact of the new railway and of the increase in the static storage capacity of the warehouses. Scenarios 4 to 8 (section 5.2.2) evaluated the minimization of total logistic cost, which is the most used objective function. Scenarios 9 to 20 (section 5.2.3) added the minimization of CO₂ emissions to the objective function and tested different weights for each component.

The expected 2035 multimodal transportation network already includes the main planned infrastructure projects. However, to better evaluate the performance and attractiveness of the proposed new railway, scenarios 21 to 28 changed waterway/cabotage and railway freight costs. Scenarios 21 to 24 (section 5.2.4) added the effects of the project “BR do Mar” to the model. This project is an initiative of the Ministry of Infrastructure with the goal of encouraging cabotage usage in Brazil, through supply increase, competition promotion, costs reduction, and routes expansion. Finally, scenarios 25 to 28 (section 5.2.5) considered a reduction in the railway freight price of 10%.

5.2.1. Scenarios 1 to 4 – 2017 data

Scenarios 1 to 4 are designed to validate the model. These scenarios have only two products (maize and soybean), use the 2017 multimodal transportation and warehouse networks, and consider only the cost component of the objective function ($\alpha = 1$ and $\beta = 0$). Scenario 1 uses the logistic network as it is, while in scenario 2 the warehouses' static capacity can be increased to their optimal volume, with no implementation cost. Scenario 3 adds the new railway to the transportation network, as designed in the first model (section 5.1.1), and scenario 4 includes both

the new railway and unconstrained warehouse static capacity. Table 21 shows the main indicators for the scenarios' solution.

Table 21. Optimization model - results of scenarios 1 to 4.

	Scenario 1: 2017 transport and warehouse networks	Scenario 2: 2017 transport network + unconstrained static capacity	Scenario 3: 2017 transport and warehouse networks + new railway	Scenario 4: 2017 transport network + new railway + unconstrained static capacity
% railway TKU	14.0%	12.5%	24.2%	24.4%
% waterway/cabotage TKU	18.6%	17.6%	15.7%	13.7%
% road TKU	67.4%	69.8%	60.0%	61.9%
Total TKU	169,022,346,112	163,508,607,052	169,960,623,173	168,849,347,719
Total freight cost (million R\$)	27,210	26,862	27,247	27,390
Total product price (million R\$)	146,794	146,336	146,440	145,508
Total taxes (million R\$)	826	735	807	730
Total storage costs (million R\$)	7,398	7,532	7,400	7,524
Total cost (million R\$)	182,228	181,465	181,893	181,151
Total maximum stored volume (t)	100,569,542	114,284,267	100,061,810	115,100,006
Total increase in static storage (t)	-	43,960,171	-	42,937,117
Number of used warehouses	153	149	153	148

The comparison between scenarios 1 and 2 shows the benefits of expanding the warehouses' static capacity. There was a significant decrease in the product price, freight costs, and taxes, as an adequate storage capacity allowed the purchase of goods when the total value of product price, freight costs, and taxes was more advantageous. As this is a minimum cost model, it is assumed that it represents the consumer behavior. If it were a producer model, it would maximize the total profit, increasing the shipments in periods of higher product price.

The reduction in total product price, freight costs, and taxes more than offset the increase in total storage costs, with a total reduction of 0.4%. In addition, there was a 3.3% reduction in total TKU, since it was more advantageous to store products in warehouses closer to the origins and the destinations (which reduces the traveled distance and the number of used warehouses). On

the other hand, shorter distances led to an increase in the road mode participation in the transportation matrix (from 67.4% to 69.8%).

The addition of the new railway had a more considerable impact on the results. The participation of the railways in the total TKU increased from 14.0% (scenario 1) to 24.2% (scenario 3), with a 0.6% increase in the total TKU as the railway increased the traveled distance. The 0.2% reduction in total costs was mainly due to the reduction in products' prices.

As expected, the minimum total cost is achieved in scenario 4, with both the new railway and unconstrained static capacity. The availability of the new railway decreased the attractiveness of using closer warehouses, and the resulting values were more similar to scenario 3 than to scenario 2. Thus, it can be said that the new railway generated a higher positive impact than the increase in warehouses' static capacity.

Table 22 shows the volume by product and by transportation mode for scenarios 1 to 4.

Table 22. Scenarios 1 to 4 - volume by product and by transportation mode (in million tonnes).

		Scenario 1: 2017 transport and warehouse networks	Scenario 2: 2017 transport network + unconstrained static capacity	Scenario 3: 2017 transport and warehouse networks + new railway	Scenario 4: 2017 transport network + new railway + unconstrained static capacity
Maize	Railway	11.0	9.8	15.1	15.6
	Waterway/Cabotage	16.3	18.0	14.2	14.0
	Rail/Water/Cabotage	0.1	0.1	-	0.0
	Road	112.8	113.8	110.9	112.1
Soybean	Railway	8.1	6.9	14.7	14.9
	Waterway/Cabotage	21.8	16.8	16.2	11.9
	Rail/Water/Cabotage	0.7	0.4	1.2	0.4
	Road	150.6	158.0	149.3	155.2
Total	Railway	19.1	16.8	29.8	30.6
	Waterway/Cabotage	38.0	34.8	30.4	25.9
	Rail/Water/Cabotage	0.8	0.5	1.2	0.4
	Road	263.4	271.8	260.2	267.3

The new railway significantly increased the volume transported by railway in 11.1 million tonnes (comparing scenario 1 and 3) and in 13.7 million tonnes (scenario 2 vs. 4) when the warehouses had unconstrained static storage capacity. Unfortunately, most of this increase came from the waterway/cabotage mode, so the road mode suffered a reduction of only 1.1% (scenario 1 vs. 3) and 1.4% (scenario 2 vs. 4) in the total volume participation.

On the other hand, the difference between the modal split in %TKU and in % tonnes showed that the new railway aided in transporting cargos for longer distances, while the road mode was used for shorter distances, as is recommended for each modal. Indeed, the average distance traveled by road decreased from 354.3 km (scenario 1) to 317.3 km (scenario 3) and from 352.5 km (scenario 2) to 322.4 km (scenario 4).

Figure 29 shows the monthly volume by product and type of flow for scenario 1. The main flows were from the origins *o* to the warehouses *j*, since the production volume is concentrated in a few months every year, so the volume not immediately consumed by the domestic or export markets must be stored in warehouses to be used in the following months (flows *jd* and *je*). The maize flows are concentrated in June and August (65.8 million tonnes, 47.0% of the total annual flow), while the soybean flows were mainly in February and April (98.2 million tonnes, 54.2%).

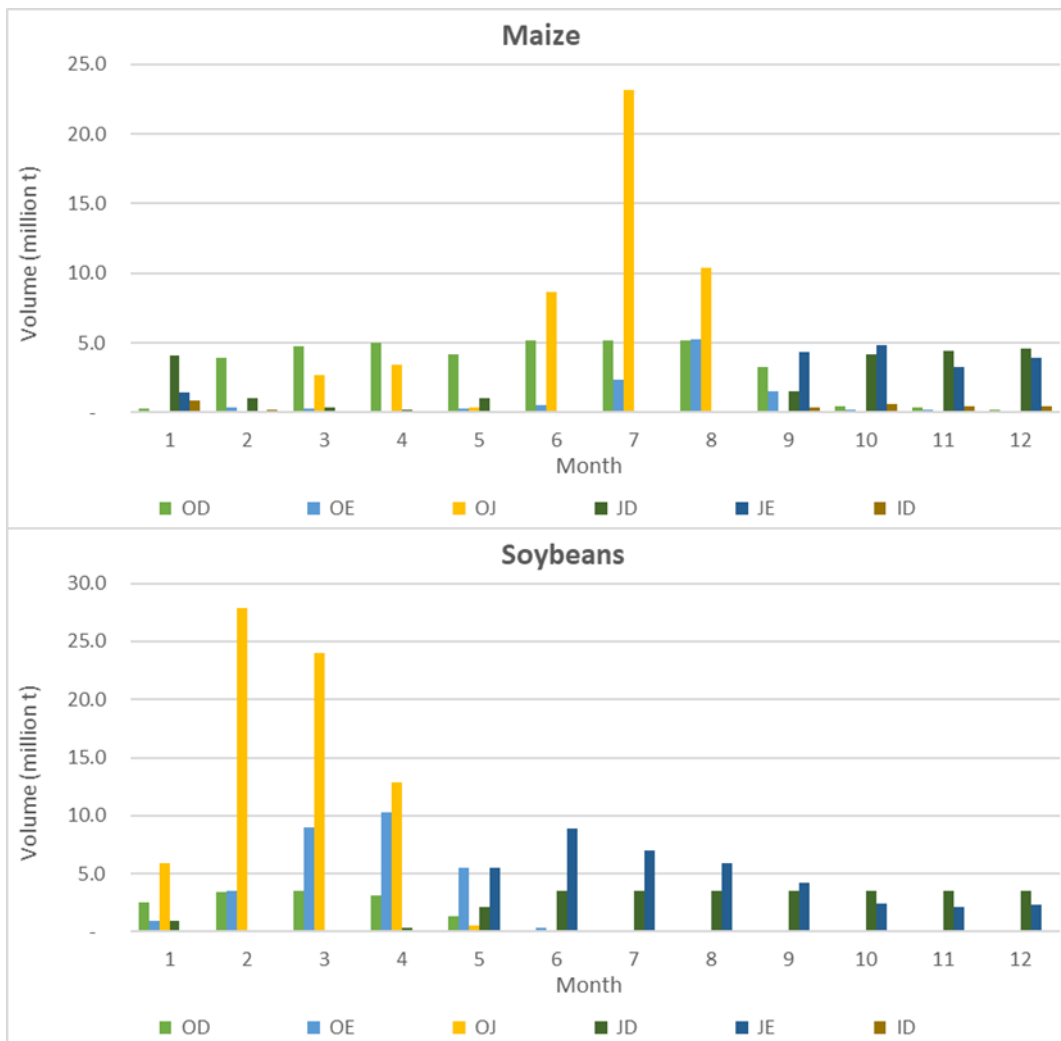


Figure 29. Scenario 1 – Monthly volume by product and by type of flow.

Lastly, the second level model generated reasonable results and can be considered as validated.

5.2.2. Scenarios 5 to 8 – 2035 data

Scenarios 5 to 8 have three products (maize, soybean, and soybean meal), use the 2035 multimodal transportation and warehouse networks, and consider only the cost component of the objective function ($\alpha = 1$ and $\beta = 0$).

Just like scenarios 1 to 4, scenario 5 uses the 2035 network as it is, while in scenario 6 the warehouses' static capacity can be increased to their optimal volume, with no implementation cost. Scenario 7 adds the new railway to the 2035 transportation network, as designed in the first model (section 5.1.1), and scenario 8 includes both the new railway and unconstrained warehouse static capacity. Table 23 presents the main indicators for the scenarios' solution.

The obtained results were very similar to that of scenarios 1 to 4, but the resulting transportation matrices (in %TKU) were more balanced than the 2017 scenarios, due to the increase in infrastructure availability, especially with the new railway (scenarios 7 and 8).

The 2035 transportation network includes several railway and waterway projects, that resulted in the higher participation of both modes in the transportation matrix (%TKU) in all scenarios. Even so, the new railway alone was responsible for increasing the railway participation in 12.2 percentage points (in %TKU), which shows the quality of the first level solution and the importance of a new railway that connects the Center-West and South regions of Brazil and also links several significant railways (Rumo Malha Norte, Rumo Malha Oeste, Pantanal Railway, FNS, and Rumo Malha Sul). The new railway was more attractive than both waterway/cabotage and road modes alternatives.

Table 23. Optimization model - results of scenarios 5 to 8.

	Scenario 5: 2035 transport and warehouse networks	Scenario 6: 2035 transport network + unconstrained static capacity	Scenario 7: 2035 transport and warehouse networks + new railway	Scenario 8: 2035 transport network + new railway + unconstrained static capacity
% railway TKU	23.4%	20.0%	35.7%	33.3%
% waterway/cabotage TKU	19.7%	19.8%	15.0%	15.5%
% road TKU	56.9%	60.2%	49.4%	51.1%
Total TKU	354,113,322,666	341,154,398,830	342,749,951,663	348,883,204,868
Total freight cost (million R\$)	56,630	55,303	55,637	56,103
Total product price (million R\$)	533,757	503,321	533,748	501,841
Total taxes (million R\$)	3,127	4,131	3,164	4,173
Total storage costs (million R\$)	11,964	11,759	11,948	11,769
Total cost (million R\$)	605,478	574,514	604,497	573,886
Total maximum stored volume (t)	135,643,692	191,137,319	135,563,608	186,487,737
Total increase in static storage (t)	-	101,391,890	-	92,992,448
Number of used warehouses	153	153	153	153
Total CO ₂ emissions (million kgCO ₂)	10,070	9,924	9,442	9,708

Table 24 shows the volume by product and by transportation mode for scenarios 5 to 8. Although the volume transported by railway significantly increased with the new railway (comparing scenarios 5 and 7 (increase of 33.3 million tonnes), and 6 and 8 (38.0 million tonnes)), the road mode was still dominant with more than 77% of the total volume. The increase in %TKU was much higher than in % volume, which shows that the new railway transported cargoes for long distances and the road mode was used for shorter distances, providing a more rational use of the modes. The average distance traveled by road decreased from 330.1 km (scenario 5) to 277.7 km (scenario 7) and from 342.4 km (scenario 6) to 296.9 km (scenario 8). In addition, these average road distances were lower than in the 2017 scenarios (1 to 4, respectively), which reinforces the importance and the benefits of expanding the multimodal transportation infrastructure.

Table 24. Scenarios 5 to 8 - volume by product and by transportation mode (in million tonnes).

		Scenario 5: 2035 transport and warehouse networks	Scenario 6: 2035 transport network + unconstrained static capacity	Scenario 7: 2035 transport and warehouse networks + new railway	Scenario 8: 2035 transport network + new railway + unconstrained static capacity
Maize	Railway	17.6	12.7	31.4	30.3
	Waterway/Cabotage	18.0	21.2	11.9	12.9
	Rail/Water/Cabotage	10.9	14.3	10.5	13.6
	Road	192.3	190.7	184.9	182.0
Soybean	Railway	20.4	12.0	39.6	30.2
	Waterway/Cabotage	30.8	27.9	15.3	17.1
	Rail/Water/Cabotage	13.9	14.4	12.7	15.3
	Road	253.2	253.8	250.3	246.4
Soybean meal	Railway	7.9	7.0	9.9	9.3
	Waterway/Cabotage	5.0	5.3	4.3	4.8
	Rail/Water/Cabotage	1.0	0.8	0.8	0.7
	Road	39.0	40.0	37.6	38.4
Total	Railway	45.9	31.7	80.9	69.7
	Waterway/Cabotage	53.8	54.4	31.5	34.7
	Rail/Water/Cabotage	25.7	29.6	24.0	29.6
	Road	484.6	484.6	472.8	466.8

The 2035 expected volumes are much higher than 2017's, so all 153 warehouses were used, even in the scenarios 6 and 8 with unconstrained static capacity. In scenarios 5 and 7 (with limited storage capacity), 144 out of 153 warehouses were used in their full capacity. In scenario 6, only 66 warehouses demanded an increase in static storage capacity, especially in the states of Mato Grosso (32.1 million tonnes), Goiás (28.0 million tonnes), Mato Grosso do Sul (12.9 million tonnes), Paraná (9.0 million tonnes), and Rio Grande do Sul (3.1 million tonnes). The municipalities with the highest increase in static storage capacity were Leopoldo de Bulhões (GO, 16.0 million tonnes), Campo Novo do Parecis (MT, 10.3 million tonnes), Barra do Garças (MT, 7.6 million tonnes), Sidrolândia (MS, 6.4 million tonnes), and Montes Claros de Goiás (GO, 4.3 million tonnes).

The results in scenario 8 were very similar to scenario 6, with 69 warehouses increasing static storage capacity, mainly in: Goiás (26.7 million tonnes), Mato Grosso (23.7 million tonnes), Mato Grosso do Sul (12.5 million tonnes), Paraná (10.1 million tonnes), and Rio Grande do Sul (3.4 million tonnes). The municipalities with the highest increase in static storage capacity were Leopoldo de Bulhões (GO, 15.7 million tonnes), Barra do Garças (MT, 7.4 million tonnes), Sinop (MT, 6.1 million tonnes), Sidrolândia (MS, 5.8 million tonnes), and Montes Claros de Goiás (GO, 4.6 million tonnes).

As the warehouses are located in the same state as the producing regions, it is expected that the states with the higher production volumes have the highest need for static storage capacity.

The monthly total stored volume by product was the same in scenarios 5 and 7, but there were variations between the states. For instance, the total stored volume of maize in Brazil by the end of September was 72.0 million tonnes in both scenarios, but in scenario 5 the maize stored volume was 12.0 million tonnes in the state of Paraná and 29.5 million tonnes in Mato Grosso, while in scenario 7 was 12.7 million tonnes and 28.6 million tonnes, respectively. These results showed that, as the only difference between scenarios 5 and 7 is the lower freight cost between the Center-West and South regions, there is an optimal monthly stored volume given the maximum capacity, so it is better to leave the goods stored in the municipalities with higher total cost (product price, freight cost, and taxes), as the unitary storage costs are very similar.

Comparing scenarios 6 and 8, the monthly total stored volume for soybean and soybean meal was the same, as were the soybean meal monthly total stored volume in scenarios 5 and 6; again, there were variations between the states.

Figure 30 shows the monthly evolution by product. For maize, the main production volume is in the second semester with the second-crop (mainly in the Center-West region and in Paraná). In the first semester, the production volume is not enough to fulfill the demand (domestic consumption plus exports), thus depleting the stored volume and relying on the imported volume. On the other hand, soybean production is only in the first semester, hence the need to use the stored volume in the second semester. Soybean meal have a flatter volume throughout the year due to the manufacturing dynamics.



Figure 30. Scenario 5 – Monthly evolution by product.

Thus, as the consumption volume is the same throughout the year and the production volume varies with the harvest months, the warehouse network is important to guarantee the supply to both domestic and export markets. The possibility of importing products is also

important, since there are periods that the stored volume is not enough to satisfy the demand, or the price is so high that it is economically unfeasible.

The monthly evolution by product is also important because maize, soybean, and soybean meal share the same multimodal and warehouse constrained infrastructure. For instance, in scenario 5 maize had the highest transported volume between June and August (122.4 million tonnes, which is 51.3% of the annual maize transported volume), with a peak of 80.5 million tonnes of volume stored in August. On the other hand, soybean highest transported volume was in February to April (181.0 million tonnes, that are 56.9% of the annual soybean transported volume), with a peak storage in April (117.8 million tonnes). Thus, the seasonality must be considered, since some infrastructures have idle capacity in some months and are overloaded in other months, while the domestic consumption and the export markets always must be fulfilled.

The seasonality of volume flows is shown in Figure 31. The most significant flows were from the origins o to warehouses j during the harvest season. As the warehouses are located in the same state as the production centers, it is a relatively short distance trip that is done almost exclusively by road and trucks. These volumes are considerably higher than of 2017, so Brazil must prepare its transportation and warehouse infrastructure to adequate their capacity to, not only provide the best option, but to not suffer from lack of capacity, which may lead to losses of products and sales.

For instance, in 2017 the highest transported volume was in March (44.6 million tonnes in scenario 1). In 2035, considering only maize and soybean, the transported peak volume was in July with 78.2 million tonnes, which is 75.1% higher than the 2017 peak value. Again, the Brazilian multimodal transportation and warehouse networks must be improved to meet the estimated volumes, or the country will suffer with overloaded infrastructures, high freight prices, and products that cannot be transported due to lack of available transportation.

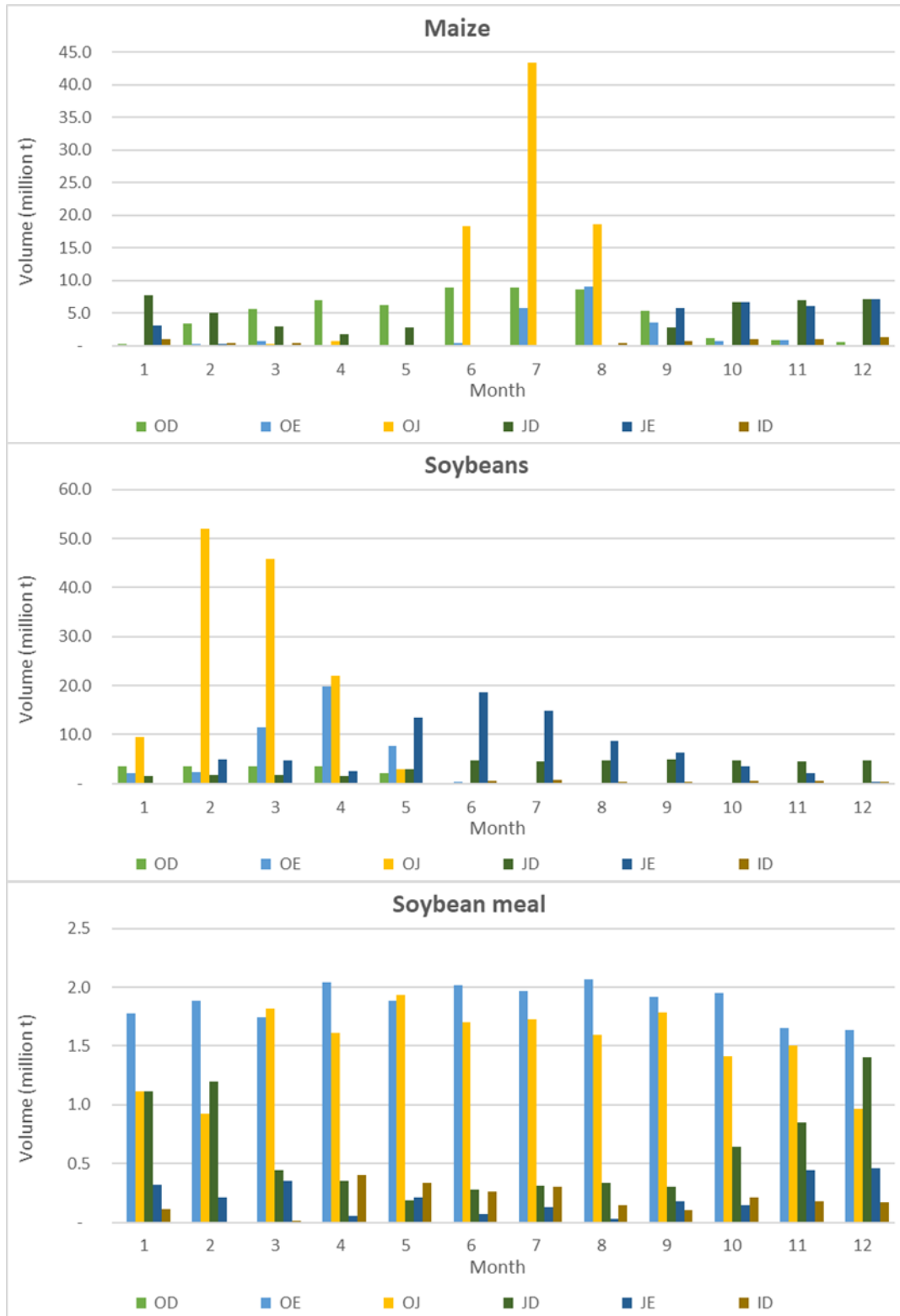


Figure 31. Scenario 5 – Monthly volume by product and by type of flow.

Regarding the transportation infrastructures with the highest volume, in scenario 5 the Rumo Malha Paulista and MRS railways’ stretch between Campinas (SP) and the port of Santos (SP) transported the highest volume, with 32.5 million tonnes along 140.4 km and more than 34.1

million tonnes in the 12.8 km closest to the port. The FCA (Center-Atlantic Railway) stretch from Pires do Rio (GO) to Campinas (SP), where it intersects with Rumo Malha Paulista, has 695.6 km and moved between 24.1 and 28.7 million tonnes. The Ferrogrão transported 21.9 million tonnes through its full extension of 857.7 km between Sinop (MT) and Itaituba (PA). The 316.1 km FNS stretch from Mara Rosa (GO) to Leopoldo de Bulhões (GO) continues to the FCA stretch from Leopoldo de Bulhões to Pires do Rio (GO, with 129.2 km), receiving more than 13.3 million tonnes of cargo.

The main waterways were Tietê-Paraná, with over 32.6 million tonnes from São Simão (GO) to Botucatu (SP) (573.2 km); Tapajós, with around 25.2 million tonnes transported between Itaituba (PA) and Santarém (PA) (extension of 251.5 km); and Amazonas; with 13.4 million tonnes between Santarém (PA) and Afuá (PA) (512.1 km).

In the road network, the 31.8 km road stretch around the port of Santos transported more than 60.1 million tonnes; the 28.3 km stretch around the port of Paranaguá carried more than 32.5 million tonnes; the 451.0 km stretch from Santa Vitória (MG) passing through the state of Goiás through São Simão and Jataí till Barra do Garças (MT) transported between 27.8 and 34.6 million tonnes; and the 94.4 km stretch across Primavera do Leste (MT) received more than 28.3 million tonnes.

In scenario 8, the new railway most used stretch was between Rondonópolis (MT) and Chapadão do Sul (MS), with 351.7 km of extension and volume ranging between 38.4 and 42.3 million tonnes. In this stretch, the new railway runs near the Rumo Malha Norte railway. The stretch from Rosário Oeste (MT) to Rondonópolis has 253.5 km and carried between 30.0 and 33.3 million tonnes. The branch from Chapadão do Sul and Aparecida do Taboado (MS), that practically overlaps with the Rumo Malha Norte, has 171.0 km and received more than 25.4 million tonnes. The 317.7 km stretch from Três Lagoas (MS) to Arapongas (PR) transported between 19.9 and 22.6 million tonnes. The least used stretch is from Chapadão do Sul to Três Lagoas, with 197.0 km of extension and 17.5 million tonnes of transported volume.

Considering its whole extension, the new railway transported 51.9 million tonnes throughout the year, with a minimum volume of 1.4 million tonnes in November and a maximum volume of 11.3 million tonnes in June. Only 9.1 million tonnes were moved to the domestic markets (flows *od* and *jd*).

Among the other railways, the Rumo Malha Paulista and MRS railways' stretch between Campinas (SP) and the port of Santos (SP) transported the highest volume, with 30.0 million tonnes along 140.4 km and more than 34.2 million tonnes in the 12.8 km closest to the port. It is followed by the adjacent stretch of Rumo Malha Paulista between Campinas and Santa Fé do Sul (SP); the

Rumo Malha Norte stretch from the intersection with Rumo Malha Paulista in Santa Fé do Sul until Aparecida do Taboado (MS) (where the cargo moved to the new railway); and the FNS stretch between Pontalinda (SP) and Urânia (SP), where it intersects with Rumo Malha Paulista. This 605.1 km stretch transported between 24.4 and 26.5 million tonnes.

The Ferrogrão transported 24.2 million tonnes through its full extension of 857.7 km between Sinop (MT) and Itaituba (PA). The Rumo Malha Sul transported around 20.6 million tonnes (that came from the new railway) between Arapongas (PR) and Balsa Nova (PR) (extension of 318.1 km), and between 15.1 and 18.0 million tonnes from Balsa Nova to the port of Paranaguá (PR) (103.6 km).

The Rumo Malha Oeste intersects with the new railway in Três Lagoas (MS), near the Rio Branco (MS) terminal. Its busiest stretches were from Três Lagoas to Campo Grande (MS), with 265.4 km and 10.8 million tonnes, and from Três Lagoas to Mirandópolis (SP), with 122.4 km and 8.6 million tonnes.

The main waterways were Tapajós, with around 27.0 million tonnes transported between Itaituba (PA) and Santarém (PA) (extension of 251.5 km); Tietê-Paraná, with over 17.4 million tonnes from São Simão (GO) to Botucatu (SP) (573.2 km); and Amazonas; with around 11.5 million tonnes between Santarém (PA) and Afuá (PA) (512.1 km).

In the road network, the stretches that transported the highest volumes are small and are located around exporting ports or the main producing areas. The 31.8 km road stretch around the port of Santos transported more than 59.9 million tonnes; the 28.3 km stretch around the port of Paranaguá carried more than 34.6 million tonnes; and the 289.9 km between Nova Mutum (MT), Lucas do Rio Verde (MT), Sorriso (MT), and Sinop (MT) transported between 20.9 and 43.0 million tonnes.

Thus, the new railway and the optimal static storage capacity, which are the changes from scenario 5 to 8, altered some of the most used transportation infrastructures. The new railway transported a significant volume, from 17.5 to 42.3 million tonnes, and helped increase the cargo carried in the railways that intersect with it. The volume transported in the Rumo Malha Norte stretch between Santa Fé do Sul (SP) and Aparecida do Taboado (MS) increased from 8.5 million tonnes in scenario 5 to 25.7 million tonnes in scenario 8. Rumo Malha Sul did not transport any cargo in scenario 5 but moved between 15.1 and 20.7 million tonnes of cargo in scenario 8 from Arapongas (PR) to the port of Paranaguá (PR). The volume moved in the Rumo Malha Oeste stretch between Campo Grande (MS) and Mirandópolis (SP) increased from 5.9 million tonnes in scenario 5 to at least 8.6 million tonnes in scenario 8.

On the other hand, the volume transported in the Tietê-Paraná waterway from São Simão (GO) to Botucatu (SP) decreased from 32.6 million tonnes in scenario 5 to over 17.4 million tonnes in scenario 8, as this stretch is relatively near to the new railway.

The imported flows are very similar in scenarios 5 to 8. The main entry points in scenario 5 were Foz do Iguaçu (PR), with 3.1 million tonnes of maize and 1.2 million tonnes of soybean; Santa Helena (PR), with 1.6 million tonnes of maize and 0.9 million tonnes of soybean; and Guáira (PR), with 0.8 million tonnes of maize and 0.7 million tonnes of soybean. These three cities are located near the Brazilian border with Paraguay, which is an important source of maize and soybean. Thus, it is interesting to improve the infrastructure especially in and around these three cities, including customs and sanitary checking's capacity, to minimize large queues at the borders.

The impact of the new railway can be measured by comparing scenarios 5 and 7, and 6 and 8, since the only difference between them is the addition of the new railway to the transportation network. Comparing scenarios 6 and 8, the addition of the new railway decreased the total costs in 0.1% (R\$ 628.1 million), the total CO₂ emissions in 2.2%, the maximum stored volume in 2.4%, and the total increase in static storage in 8.3%; and increased the total TKU in 2.3% and the volume transported by railways in 38.0 million tonnes, that came from a reduction in the use of waterways/cabotage (19.7 million tonnes) and road modes (17.8 million tonnes). Considering only the domestic market flows (*od*, *oe*, and *id*), there was a reduction of 0.2% in total costs (R\$ 411.1 million) and of 2.7% in CO₂ emissions. Thus, the new railway improved the Brazilian logistics network for the domestic market of agricultural products in a more sustainable way.

The improvements are rather small; however, were more significant for the domestic market flows. The impact of the increase in the static storage capacity offsets the effect of the new railway, which reinforces the need of several strategies to improve the Brazilian logistics network. On the other hand, if the flows to export markets and warehouses and the storage costs are also considered, the positive impact of the new railway is higher. It is also a reflection of the proposed model, that optimizes both the flows to the domestic and export markets as well as costs associated with the storage. Although the new railway was designed with the objective of improving the domestic market supply, it also improved the access to the export markets, helping Brazil achieve a more rational and balanced transportation matrix.

5.2.3. Scenarios 9 to 20 – 2035 data and CO₂ emissions

Scenarios 9 to 12 have the same parameters and configurations as scenarios 5 to 8,

respectively, but consider only the CO₂ emissions component of the objective function ($\alpha = 0$ and $\beta = 1$). Table 25 shows the main indicators for the scenarios' solution.

Table 25. Optimization model - results of scenarios 9 to 12.

	Scenario 9: 2035 transport and warehouse networks + only CO ₂ emissions	Scenario 10: 2035 transport network + unconstrained static capacity + only CO ₂ emissions	Scenario 11: 2035 transport and warehouse networks + new railway + only CO ₂ emissions	Scenario 12: 2035 transport network + new railway + unconstrained static capacity + only CO ₂ emissions
% railway TKU	39.6%	36.3%	40.9%	39.8%
% waterway/cabotage TKU	27.5%	29.4%	23.8%	25.6%
% road TKU	32.9%	34.3%	35.3%	34.5%
Total TKU	359,147,456,823	313,995,098,412	330,766,415,785	299,894,171,614
Total freight cost (million R\$)	54,574	50,153	52,706	49,504
Total product price (million R\$)	549,376	551,382	550,032	551,006
Total taxes (million R\$)	5,650	6,162	5,624	5,979
Total storage costs (million R\$)	11,788	11,882	11,789	11,942
Total cost (million R\$)	621,387	619,579	620,152	618,431
Total maximum stored volume (t)	135,783,368	177,105,145	135,746,986	175,987,801
Total increase in static storage (t)	-	76,358,003	-	74,669,499
Number of used warehouses	153	153	153	152
Total CO ₂ emissions (million kgCO ₂)	8,212 (-18.5%)	7,200 (-27.4%)	7,859 (-16.8%)	7,021 (-27.7%)

It can be said that scenarios 9 to 12 present the best solution in an environmental perspective. Scenario 11 presented the smaller reduction in CO₂ emissions (16.8%), while scenario 12 had the highest decrease (27.7%), compared to scenarios 7 and 8, respectively. The participation of railway and waterway/cabotage modes in the transportation matrix (in %TKU) significantly increased, as their CO₂ emission rate is much lower than that of the road mode, which has a participation of only 35%. Every municipality can access the railway or the waterway/cabotage

network; however, the long distances to reach a port or a terminal can hinder their feasibility, depending on the objective function.

Although the waterway/cabotage modes are less expensive and have a lower CO₂ emission rate than railways, its network infrastructure is limited to the existing rivers and the seacoast, which limits their area of influence; while railways can, theoretically, be built in any location of the country. In addition, there is the seasonality, as some waterways must be closed during the dry season.

In general, when the CO₂ emissions are considered in the objective function, it is better to purchase goods from a closer production area, warehouse, or entry point to reduce the traveled distance, even if the product price plus taxes are higher; and it is better to use the railway and waterway/cabotage modes, since they have a lower emission rate than the road mode.

In scenarios 10 to 12, there was a significant reduction in the total TKU in comparison with scenarios 6 to 8, respectively, as shorter travels generate less CO₂ emissions. The most substantial reduction was in scenario 12, with a total TKU 14.0% lower than scenario 8. On the other hand, scenarios 9 to 12 have a substantial increase in the total costs of 2.6% for scenarios 9 and 11 and 7.8% for scenarios 10 and 12 (in comparison with scenarios 5 to 8, respectively). There was a decrease in freight costs and storage costs (for scenarios 9 and 11), and an increase in product costs, taxes, and storage costs (for scenarios 10 and 12). Hence, it is interesting to balance costs and CO₂ emissions, which will be achieved by varying the α and β weights in the following scenarios.

Comparing scenarios 8 and 12 (using scenario 8 as reference), there are small differences in the volumes per type of shipment (*od, oe, oj, jd, je, id*). The substantial reduction in the road TKU of 74.8 billion TKU (especially from warehouses *j* to exporting ports *e* (26.2 billion TKU)) more than offsets the increases in railway TKU (3.1 billion TKU) and waterway/cabotage TKU (22.7 billion TKU), which is also mainly from warehouses *j* to exporting ports *e* (18.5 billion TKU).

When the objective function is to minimize the CO₂ emissions, the impact of the new railway is much lower than when the objective is to minimize the costs (scenarios 5 to 8). For the expected warehouse network capacity, the new railway increases the railway mode participation (in %TKU) in only 1.3 percentage point (scenario 9 vs. scenario 11). Its impact is higher for the unconstrained warehouse network capacity (3.5 percentage points, for scenario 10 vs. scenario 12), but still much lower than the scenarios with the cost minimization (12.2 percentage points and 13.3 percentage points, respectively). This difference can be explained by the fact that the new railway connects the domestic market of distant municipalities in the Center-West and South regions, while long travels are discouraged to minimize the CO₂ emissions.

Scenarios 13 to 16 have the same parameters and configurations as scenarios 9 to 12, respectively, but consider both costs and CO₂ emissions components of the objective function with equal weight ($\alpha = 1$ and $\beta = 1$). Table 26 presents the main indicators for the scenarios' solution.

Table 26. Optimization model - results of scenarios 13 to 16.

	Scenario 13: 2035 transport and warehouse networks + $\alpha=1$ and $\beta=1$	Scenario 14: 2035 transport network + unconstrained static capacity + $\alpha=1$ and $\beta=1$	Scenario 15: 2035 transport and warehouse networks + new railway + $\alpha=1$ and $\beta=1$	Scenario 16: 2035 transport network + new railway + unconstrained static capacity + $\alpha=1$ and $\beta=1$
% railway TKU	29.5%	27.9%	38.8%	34.5%
% waterway/cabotage TKU	21.4%	19.6%	16.9%	16.9%
% road TKU	49.1%	52.6%	44.3%	48.5%
Total TKU	352,095,707,028	321,197,700,406	338,254,254,114	324,726,040,102
Total freight cost (million R\$)	55,723	52,824	54,684	53,411
Total product price (million R\$)	535,129	506,634	535,085	505,148
Total taxes (million R\$)	3,022	3,834	3,079	3,967
Total storage costs (million R\$)	11,924	11,731	11,907	11,752
Total cost (million R\$)	605,798	575,023	604,755	574,278
Total maximum stored volume (t)	135,404,799	182,236,089	135,390,172	183,479,753
Total increase in static storage (t)	-	92,363,480	-	92,256,050
Number of used warehouses	153	153	153	153
Total CO ₂ emissions (million kgCO ₂)	9,413	8,871	8,909	8,818

In scenarios 13 to 16, the resulting transportation matrices are even more balanced than in scenarios 5 to 8, as a reflection of the concern with the CO₂ emissions. There was also a significant decrease in the total TKU in comparison with scenarios 5 to 8, respectively, but lower than that of scenarios 10 to 12. The most substantial reduction was in scenario 16, with a total TKU 6.9% lower than scenario 8.

The new railway has a significant impact on the railway mode participation in the transportation matrix, as it is responsible for a 9.3 percentage points and a 6.7 percentage points increase in %TKU (comparing scenarios 13 and 15 and scenarios 14 and 16, respectively).

The total CO₂ emissions value (around 9 billion kgCO₂) are much lower than the total costs value (around R\$ 600 billion), so even though their weights are equal ($\alpha = 1$ and $\beta = 1$), the optimal solutions are more similar to the scenarios of minimal cost (scenarios 5 to 8) than that of minimal CO₂ emissions (scenarios 9 to 12). The total costs only increased 0.1% (comparing with scenarios 5 to 8), while the total CO₂ emissions increased from 13.4% to 25.6% (in comparison with scenarios 9 to 12).

Thus, in the next scenarios, different weights are tested, to better evaluate the difference between minimal costs' and CO₂ minimal emissions' solutions. Scenarios 17 to 20 have the same parameters and configurations as scenario 16 and the only difference is the value of β (5, 15, 30, and 65, respectively). Scenario 16 was chosen as reference since it provided the solution with the lowest value of the objective function. Table 27 shows the main indicators for the scenarios' solution.

As β increases, the scenarios' results are more similar to scenario 12 (only CO₂ emissions). The idea is to achieve a balance between minimal costs and minimal CO₂ emissions, so scenario 18 is chosen ($\alpha = 1$ and $\beta = 15$), since there was a small increase in costs (0.9% of scenario 8 total costs) and a substantial decrease in CO₂ emissions (9.5% of scenario 12 total CO₂ emissions). In this scenario, the railway participation in the transportation matrix is very high (39.6% in %TKU), which shows the positive impact of the new railway.

Table 27. Optimization model - results of scenarios 17 to 20.

	Scenario 17: 2035 transport network + new railway + unconstrained static capacity + $\alpha=1$ and $\beta=5$	Scenario 18: 2035 transport network + new railway + unconstrained static capacity + $\alpha=1$ and $\beta=15$	Scenario 19: 2035 transport network + new railway + unconstrained static capacity + $\alpha=1$ and $\beta=30$	Scenario 20: 2035 transport network + new railway + unconstrained static capacity + $\alpha=1$ and $\beta=65$
% railway TKU	36.5%	39.6%	41.0%	42.3%
% waterway/cabotage TKU	20.3%	21.8%	22.1%	22.6%
% road TKU	43.2%	38.5%	36.9%	35.1%
Total TKU	310,091,063,742	312,018,111,073	305,676,406,379	300,917,656,353
Total freight cost (million R\$)	51,341	51,108	50,461	49,970
Total product price (million R\$)	509,285	511,803	518,312	528,877
Total taxes (million R\$)	3,805	3,996	4,048	4,256
Total storage costs (million R\$)	11,812	11,881	11,953	12,039
Total cost (million R\$)	576,243	578,787	584,774	595,143
Total maximum stored volume (t)	179,562,504	177,668,395	179,623,126	181,564,022
Total increase in static storage (t)	82,533,795	78,082,144	76,710,976	77,454,486
Number of used warehouses	153	153	153	152
Total CO ₂ emissions (million kgCO ₂)	7,976	7,688	7,422	7,189
Increase total cost - scenario 8 (%)	0.4%	0.9%	1.9%	3.7%
Increase total CO ₂ emissions - scenario 12 (%)	13.6%	9.5%	5.7%	2.4%

Comparing the transported volumes in scenario 18 with scenario 8, there was a small increase in the cargo transported by railway (1.0 million tonnes) and a significant increase in the volume transported by both railway and waterway/cabotage (16.5 million tonnes), which led to a 20.8% reduction in CO₂ emissions (vs. scenario 8). The road mode was still dominant with 76.0% of the total volume (vs. 77.7% in scenario 8), but the average distance traveled by road decreased to only 199.0 km (vs. 296.9 km in scenario 8).

In scenario 18, there were 58 warehouses increasing static storage capacity, mainly in: Mato Grosso (28.2 million tonnes), Goiás (25.4 million tonnes), Paraná (5.1 million tonnes), and Rio Grande do Sul (4.6 million tonnes). The municipalities with the highest increase in static storage capacity were Anápolis (GO, 10.9 million tonnes), Leopoldo de Bulhões (GO, 9.6 million tonnes), Querência (MT, 6.9 million tonnes), São Felix do Araguaia (MT, 6.2 million tonnes), and Soledade (RS, 4.1 million tonnes). Thus, the addition of CO₂ emissions in the objective function resulted in a very different optimal solution.

The volume transported in the new railway in scenario 18 was of at least 6.2 million tonnes, which is a remarkable value but is much lower than the minimum volume of 17.5 million tonnes of scenario 8. The new railway most used stretch was between Chapadão do Sul (MS) and Sonora (MS). This 223.4 km stretch transported between 26.0 and 28.5 million tonnes. The branch from Chapadão do Sul and Aparecida do Taboado (MS) has 171.0 km and received between 22.9 and 23.8 million tonnes. The 128.3 km stretch from Sonora to Rondonópolis (MT) carried 21.3 million tonnes and the 253.5 km stretch from Rondonópolis to Rosário Oeste (MT) transported over 14.9 million tonnes. Next, is the stretch from Presidente Venceslau (SP) to Arapongas (PR), with 186.0 km of extension and volume ranging between 11.5 and 12.9 million tonnes. The least used stretch is from Chapadão do Sul to Presidente Venceslau, with 328.7 km of extension and over 6.2 million tonnes of transported volume.

Considering its whole extension, the new railway transported 40.0 million tonnes throughout the year, with a minimum volume of 1.1 million tonnes in November and December and a maximum volume of 7.8 million tonnes in June. Only 6.5 million tonnes were moved to the domestic markets (flows *od*, *jd* and *id*).

Among the other railways, the Rumo Malha Paulista and MRS railways' stretch between Campinas (SP) and the port of Santos (SP) transported the highest volume, with 34.3 million tonnes along 140.4 km and more than 43.7 million tonnes in the 12.8 km closest to the port. It is followed by the Ferrogrão, that transported 34.0 million tonnes through its full extension of 857.7 km between Sinop (MT) and Itaituba (PA).

The stretches of Rumo Malha Paulista between Campinas and Santa Fé do Sul (SP); of Rumo Malha Norte from the intersection with Rumo Malha Paulista in Santa Fé do Sul until Aparecida do Taboado (MS) (where the cargo moved to the new railway); and of FNS between Pontalinda (SP) and Urânia (SP), where it intersects with Rumo Malha Paulista, transported over 23.3 million tonnes over an extension of 605.1 km.

The Rumo Malha Oeste from Campo Grande (MS) to the port of Santos (SP) has 1,077.5 km and moved between 14.8 and 15.9 million tonnes. It intersects with the new railway in Três Lagoas (MS), near the Rio Branco (MS) terminal.

The FCA stretch from Anápolis (GO) to Campinas, where it intersects with Rumo Malha Paulista and continues towards the port of Santos, has 837.1 km and moved between 11.1 and 14.8 million tonnes. The Rumo Malha Sul transported around 12.1 million tonnes (that came from the new railway) between Arapongas (PR) and Balsa Nova (PR) (extension of 318.1 km), and over 9.8 million tonnes from Balsa Nova to the port of Paranaguá (PR) (103.6 km).

The main waterways were Tapajós, with around 34.1 million tonnes transported between Itaituba (PA) and Santarém (PA) (extension of 251.5 km); Amazonas; with 18.9 million tonnes between Santarém (PA) and Afuá (PA) (512.1 km); Tocantins; with over 16.0 million tonnes between Almeirim (PA) and Barcarena (PA) and Belém (PA) (459.1 km); and Tietê-Paraná, with over 10.3 million tonnes from São Simão (GO) to Botucatu (SP) (573.2 km).

In the road network, the stretches that transported the highest volumes are small and are located around exporting ports or the main producing areas. The 31.8 km road stretch around the port of Santos transported more than 59.3 million tonnes; the 28.3 km stretch around the port of Paranaguá carried more than 32.5 million tonnes; the 130.8 km between Sorriso (MT) and Sinop (MT) transported between 21.8 and 40.1 million tonnes; and the 19.2 km stretch near the port of Itaituba (PA) received 34.1 million tonnes.

The main entry points of imported products in scenario 18 were also Foz do Iguaçu (PR), with 3.3 million tonnes of maize and 1.7 million tonnes of soybean; Santa Helena (PR), with 1.7 million tonnes of maize and 1.1 million tonnes of soybean; and Guaíra (PR), with 0.8 million tonnes of maize and 0.8 million tonnes of soybean.

To better assess the impact of the new railway, a scenario with the 2035 transport network, unconstrained static storage capacity, and weights $\alpha=1$ and $\beta=15$ was executed. The addition of the new railway decreased the total TKU in 2.4%, the total costs in 0.1% (R\$ 444.9 million), the total CO₂ emissions in 2.0%, the maximum stored volume in 0.9%, and the total increase in static storage in 3.8%; and increased the volume transported by railways in 24.6 million tonnes, although most of the increase came from a reduction in the use of waterways/cabotage (21.6 million tonnes). Considering only the domestic market flows (*od*, *oe*, and *id*), there was a reduction of 0.2% in total costs (R\$ 400.9 million) and of 4.5% in CO₂ emissions. Thus, the new railway had a greater positive impact in the domestic market flows and improved the Brazilian logistics network for the domestic market of agricultural products in a more sustainable way.

5.2.4. Scenarios 21 to 24 – 2035 data and “BR do Mar”

The robustness of the new railway can be evaluated by analyzing the impacts of adding a competitive alternative. One option is the “BR do Mar”, which is simulated through a 15% decrease in the waterway/cabotage freight costs (EPL, 2021a) in scenarios 21 to 24. These scenarios have the same parameters and configurations as scenarios 5, 7, 8, and 18, except for the waterway/cabotage freight cost. Table 28 shows the data for the scenarios’ solution.

Table 28. Optimization model - results of scenarios 21 to 24.

	Scenario 21: 2035 transport and warehouse networks + “BR do Mar”	Scenario 22: 2035 transport and warehouse networks + new railway + “BR do Mar”	Scenario 23: 2035 transport network + new railway + unconstrained static capacity + “BR do Mar”	Scenario 24: 2035 transport network + new railway + unconstrained static capacity + $\alpha=1$ and $\beta=15$ + “BR do Mar”
% railway TKU	17.8% (-5.7pp)	31.7% (-3.9pp)	29.5% (-3.8pp)	38.0% (-1.6pp)
% waterway/cabotage TKU	25.6% (+5.9pp)	19.5% (+4.6pp)	20.5% (+4.9pp)	23.6% (1.8pp)
% road TKU	56.6% (-0.2pp)	48.8% (-0.6pp)	50.0% (-1.1pp)	38.4% (-0.1pp)
Total TKU	362,925,530,562	350,177,064,153	359,299,765,176	313,712,846,518
Total freight cost (million R\$)	56,051	55,235	55,830	50,557
Total product price (million R\$)	533,657	533,660	501,642	511,755
Total taxes (million R\$)	3,113	3,177	4,142	4,010
Total storage costs (million R\$)	11,968	11,934	11,742	11,882
Total cost (million R\$)	604,788	604,005	573,356	578,203
Total maximum stored volume (t)	135,657,348	135,514,887	186,916,165	176,869,464
Total increase in static storage (t)	-	-	94,354,882	79,139,316
Number of used warehouses	153	153	153	153
Total CO ₂ emissions (million kgCO ₂)	10,053 (-0.2%)	9,416 (-0.3%)	9,709 (+0.0%)	7,655 (-0.4%)

The “BR do Mar” is an ongoing initiative from the Brazilian government to stimulate the cabotage mode by increasing supply and competitiveness, reducing costs, and expanding routes.

There are four main pillars: fleet, costs, ports, and naval industry. It is expected to simplify labor relationships, change taxes, reduce bureaucracy, and decrease time of cargo and ship on the port. Thus, it was concluded that the “BR do Mar” can generate a 15% reduction in the waterway/cabotage freight costs (EPL, 2021a). Annex B shows the Brazil’s 2035 expected cabotage routes and ports.

As expected, compared to scenarios 5, 7, 8, and 18, there was an increase in the participation of the waterway/cabotage mode in the transportation matrix (in %TKU), that came mainly from the flows transferred from the railway mode. As the road modal share had a small variation, the total CO₂ emissions also had a small reduction. The most significant change was an increase in the total TKU of 3.0% in scenario 23.

However, the highest increase of the cabotage mode was in scenario 21 (without the new railway) and the lowest was in scenario 24 (with the new railway and balancing costs and CO₂ emissions). In addition, even with the “BR do Mar” increasing the cabotage competitiveness, the new railway was responsible for a 14.0 percentage points increase of the railway mode participation (in %TKU, comparing scenario 21 and 22). Therefore, as the railway mode participation is still high in the scenarios with the new railway (from 29.5% to 38.0%), the results show the robustness of the proposed new railway and its substantial impact towards a more balanced transportation matrix.

Comparing the transported volumes in scenario 24 with scenario 18, there was a 3.1 million tonnes decrease in the cargo transported by railway and a significant increase in the volume transported by waterway/cabotage (11.1 million tonnes). The road mode was still dominant with 74.7% of the total volume (vs. 76.0% in scenario 18), but the average distance traveled by road (199.4 km in scenario 24 vs. 199.0 km in scenario 18) and the total CO₂ emissions (reduction of 0.4%) were practically the same.

In scenario 24, the addition of the “BR do Mar” resulted in an optimal solution very similar to that of scenario 18. In scenario 24, there were 60 warehouses increasing static storage capacity, mainly in: Mato Grosso (28.5 million tonnes), Goiás (25.7 million tonnes), Paraná (6.0 million tonnes), and Rio Grande do Sul (5.6 million tonnes). The municipalities with the highest increase in static storage capacity were Leopoldo de Bulhões (GO, 11.4 million tonnes), Anápolis (GO, 9.0 million tonnes), Querência (MT, 6.9 million tonnes), São Felix do Araguaia (MT, 6.2 million tonnes), and Soledade (RS, 4.1 million tonnes).

The new railway most used stretch in scenario 24 was between Chapadão do Sul (MS) and Sonora (MS), where the new railway intersects with the Rumo Malha Norte railway. This 223.4 km stretch transported between 24.8 and 27.25 million tonnes. The branch from Chapadão do Sul

and Aparecida do Taboado (MS) has 171.0 km and received 21.5 million tonnes. The 128.3 km stretch from Sonora to Rondonópolis (MT) carried 20.3 million tonnes and the 253.5 km stretch from Rondonópolis to Rosário Oeste (MT) transported over 14.4 million tonnes. Next, is the stretch from Presidente Venceslau (SP) to Arapongas (PR), with 186.0 km of extension and volume ranging between 11.9 and 13.0 million tonnes. The least used stretch is from Chapadão do Sul to Presidente Venceslau, with 328.7 km of extension and over 7.1 million tonnes of transported volume.

Considering its whole extension, the new railway transported 38.1 million tonnes throughout the year, with a minimum volume of 0.6 million tonnes in December and a maximum volume of 7.4 million tonnes in June. Only 6.7 million tonnes were moved to the domestic markets (flows *od*, *jd* and *id*).

Among the other railways, the MRS railway's 12.8 km stretch close to the port of Santos (SP) transported more than 42.0 million tonnes. It is followed by the Ferrogrão, that transported 34.0 million tonnes through its full extension of 857.7 km between Sinop (MT) and Itaituba (PA).

The Rumo Malha Paulista stretch between Campinas (SP) and the port of Santos carried 31.0 million tonnes along 140.4 km and the stretches of Rumo Malha Paulista between Campinas and Santa Fé do Sul (SP); of Rumo Malha Norte from the intersection with Rumo Malha Paulista in Santa Fé do Sul until Aparecida do Taboado (MS) (where the cargo moved to the new railway); and of FNS between Pontalinda (SP) and Urânia (SP), where it intersects with Rumo Malha Paulista, transported over 20.7 million tonnes over an extension of 605.1 km.

The Rumo Malha Oeste from Campo Grande (MS) to the port of Santos (SP) has 1,077.5 km and moved between 15.4 and 16.3 million tonnes. It intersects with the new railway in Três Lagoas (MS), near the Rio Branco (MS) terminal.

The FCA stretch from Anápolis (GO) to Campinas, where it intersects with Rumo Malha Paulista and continues towards the port of Santos, has 837.1 km and moved between 10.3 and 13.7 million tonnes. The Rumo Malha Sul transported 12.6 million tonnes (that came from the new railway) between Arapongas (PR) and Balsa Nova (PR) (extension of 318.1 km), and over 10.7 million tonnes from Balsa Nova to the port of Paranaguá (PR) (103.6 km).

The main waterways were Tapajós, with over 34.1 million tonnes transported between Itaituba (PA) and Santarém (PA) (extension of 251.5 km); Amazonas; with 19.3 million tonnes between Santarém (PA) and Afuá (PA) (512.1 km); Tietê-Paraná, with 14.8 to 17.3 million tonnes from São Simão (GO) to Botucatu (SP) (573.2 km); and Tocantins, with over 16.9 million tonnes between Almeirim (PA) and Barcarena (PA) (459.1 km).

In the road network, the stretches that transported the highest volumes are small and are located around exporting ports or the main producing areas. The 31.8 km road stretch around the port of Santos transported more than 59.3 million tonnes; the 28.3 km stretch around the port of Paranaguá carried more than 32.7 million tonnes; the 130.8 km between Sorriso (MT) and Sinop (MT) transported between 21.8 and 40.1 million tonnes; and the 19.2 km stretch near the port of Itaituba (PA) received 34.1 million tonnes.

The imported volume by product, month, and entry point in scenario 24 were the same as in scenario 18.

To better assess the impact of the new railway, a scenario with the 2035 transportation network and the “BR do Mar”, unconstrained static storage capacity, and weights $\alpha=1$ and $\beta=15$ was executed. The addition of the new railway decreased the total TKU in 2.7%, the total costs in 0.1% (R\$ 420.7 million), the total CO₂ emissions in 2.7%, the maximum stored volume in 0.7%, and the total increase in static storage in 2.6%; and increased the volume transported by railways in 18.4 million tonnes, although most of the increase came from a reduction in the use of waterways/cabotage (11.8 million tonnes). Considering only the domestic market flows (*od*, *oe*, and *id*), there was a reduction of 0.3% in total costs (R\$ 763.3 million) and of 4.0% in CO₂ emissions. Thus, the new railway had a greater positive impact in the domestic market flows and improved the Brazilian logistics network for the domestic market of agricultural products in a more sustainable way.

5.2.5. Scenarios 25 to 28 – 2035 data and lower railway freight

To perform a sensitivity analysis and to verify the robustness of the solution, the railway freight cost is reduced to 60% of the road freight cost in scenarios 25 to 28. These scenarios have the same parameters and configurations as scenarios 5, 7, 8, and 18, respectively, except for the railway freight cost. Table 29 shows the main indicators for the scenarios’ solution.

There was a substantial increase of the railway participation (in %TKU) in the transportation matrix compared to scenarios 5, 7, 8, and 18, respectively, that came mainly from a reduction in the road mode participation. Even so, the new railway increased the railway modal share in 3.4 percentage points. These results confirm the quality and stability of the proposed new railway.

Table 29. Optimization model - results of scenarios 25 to 28.

	Scenario 25: 2035 transport and warehouse networks + Rail freight 60%	Scenario 26: 2035 transport and warehouse networks + new railway + Rail freight 60%	Scenario 27: 2035 transport network + new railway + unconstrained static capacity + Rail freight 60%	Scenario 28: 2035 transport network + new railway + unconstrained static capacity + $\alpha=1$ and $\beta=15$ + Rail freight 60%
% railway TKU	46.4% (+23.0pp)	49.8% (+14.1pp)	48.8% (+15.5pp)	48.3% (+8.7pp)
% waterway/cabotage TKU	15.4% (-4.3pp)	12.4% (-2.6pp)	13.6% (-2.0pp)	20.7% (-1.1pp)
% road TKU	38.1% (-18.7pp)	37.8% (-11.5pp)	37.6% (-13.5pp)	31.0% (-7.6pp)
Total TKU	369,305,345,909	354,582,208,185	372,179,673,110	313,766,013,116
Total freight cost (million R\$)	55,227	54,208	55,678	49,345
Total product price (million R\$)	533,488	533,251	500,217	511,588
Total taxes (million R\$)	3,106	3,158	4,224	3,981
Total storage costs (million R\$)	11,970	11,946	11,798	11,843
Total cost (million R\$)	603,790	602,563	571,916	576,758
Total maximum stored volume (t)	135,608,947	135,559,812	188,338,724	178,632,205
Total increase in static storage (t)	-	-	92,577,401	81,406,371
Number of used warehouses	153	153	153	153
Total CO ₂ emissions (million kgCO ₂)	9,349	9,083	9,468	7,310

Table 30 shows the volume by product and by transportation mode for scenarios 25 to 28. As in the previous scenarios, although there was a remarkable increase in the volume transported by the railway (between 39.9 million tonnes in scenario 28 and 68.4 million tonnes in scenario 25), which came mainly from a reduction in the volume shipped by road, the road mode is still dominant with more than 70% of the total volume. There was also an outstanding decrease in the average distance traveled by road to only 161.2 km (vs. 199.0 km in scenario 18) that reinforces a more balanced use of the transportation modes.

Table 30. Scenarios 25 to 28 - volume by product and by transportation mode (in million tonnes).

		Scenario 25: 2035 transport and warehouse networks + Rail freight 60%	Scenario 26: 2035 transport and warehouse networks + new railway + Rail freight 60%	Scenario 27: 2035 transport network + new railway + unconstrained static capacity + Rail freight 60%	Scenario 28: 2035 transport network + new railway + unconstrained static capacity + $\alpha=1$ and $\beta=15$ + Rail freight 60%
Maize	Railway	38.0	46.3	44.4	35.9
	Waterway/Cabotage	10.3	7.9	7.8	11.9
	Rail/Water/Cabotage	12.6	11.0	14.3	17.8
	Road	177.9	173.7	172.2	174.8
Soybean	Railway	51.4	60.2	58.2	58.3
	Waterway/Cabotage	12.6	9.5	12.2	10.6
	Rail/Water/Cabotage	24.1	17.1	22.9	29.8
	Road	230.4	230.9	216.9	210.8
Soybean meal	Railway	12.9	14.1	13.7	13.6
	Waterway/Cabotage	4.0	4.1	4.3	4.8
	Rail/Water/Cabotage	1.0	0.9	0.9	1.3
	Road	34.9	33.6	34.5	33.0
Total	Railway	102.3	120.7	116.3	107.8
	Waterway/Cabotage	26.9	21.5	24.2	27.4
	Rail/Water/Cabotage	37.7	29.0	38.1	48.9
	Road	443.2	438.1	423.6	418.6

It is important to note that all scenarios consider unconstrained capacity of the transportation network, which is not consistent with the reality. However, as this is a strategic level model, these results show the potential of the multimodal transportation network and the infrastructures with the highest cargo potential.

In scenario 28, there were 53 warehouses increasing static storage capacity, mainly in: Mato Grosso (29.5 million tonnes), Goiás (25.5 million tonnes), Paraná (5.9 million tonnes), and Rio Grande do Sul (4.9 million tonnes). The municipalities with the highest increase in static storage capacity were Anápolis (GO, 14.3 million tonnes), Campo Novo do Parecis (MT, 8.0 million tonnes), Leopoldo de Bulhões (GO, 6.7 million tonnes), São Felix do Araguaia (MT, 6.3 million tonnes), and Soledade (RS, 4.0 million tonnes).

The volume transported in the new railway in scenario 28 was of at least 3.8 million tonnes, which is close to the minimum link volume of 3.5 million tonnes (Isler et al., 2021). The new railway most used stretch was between Chapadão do Sul (MS) and Sonora (MS). This 223.4 km stretch transported between 21.5 and 23.9 million tonnes. The branch from Chapadão do Sul

and Aparecida do Taboado (MS) has 171.0 km and received over 19.2 million tonnes. The 128.3 km stretch from Sonora to Rondonópolis (MT) carried 17.3 million tonnes and the 186.0 km stretch from Presidente Venceslau (SP) to Arapongas (PR) transported between 10.0 and 11.6 million tonnes. Next, is the stretch from Rondonópolis to Rosário Oeste (MT), with 253.5 km of extension and volume over 10.2 million tonnes. The least used stretch is from Chapadão do Sul to Presidente Venceslau, with 328.7 km of extension and between 3.8 and 5.2 million tonnes of transported volume.

Considering its whole extension, the new railway transported 36.4 million tonnes throughout the year, with a minimum volume of 1.3 million tonnes in November and December and a maximum volume of 7.6 million tonnes in June. Only 8.2 million tonnes were moved to the domestic markets (flows *od* and *jd*).

Among the other railways, the Rumo Malha Paulista and MRS railways' stretch between Campinas (SP) and the port of Santos (SP) transported the highest volume, with 43.8 million tonnes along 140.4 km and more than 48.9 million tonnes in the 12.8 km closest to the port. It is followed by the Ferrogrão, that transported 33.3 million tonnes through its full extension of 857.7 km between Sinop (MT) and Itaituba (PA).

The Rumo Malha Sul transported around 28.1 million tonnes between Ponta Grossa (PR) and Balsa Nova (PR) (extension of 62.1 km), over 19.6 million tonnes from Balsa Nova to the port of Paranaguá (PR) (103.6 km), 19.4 million tonnes from Apucarana (PR) to Ponta Grossa (244.9 km), and 14.1 million tonnes from Arapongas (PR) to Apucarana (only 11.0 km), that came from the new railway.

The FCA stretch from Anápolis (GO) to Campinas, where it intersects with Rumo Malha Paulista and continues towards the port of Santos, has 837.1 km and moved between 18.3 and 25.3 million tonnes.

The stretches of Rumo Malha Paulista between Campinas and Santa Fé do Sul (SP); of Rumo Malha Norte from the intersection with Rumo Malha Paulista in Santa Fé do Sul until Aparecida do Taboado (MS) (where the cargo moved to the new railway); and of FNS between Pontalinda (SP) and Urânia (SP), where it intersects with Rumo Malha Paulista, transported 19.5 to 22.2 million tonnes over an extension of 605.1 km.

The Rumo Malha Oeste from Campo Grande (MS) to the port of Santos (SP) has 1,077.5 km and moved between 13.2 and 15.8 million tonnes. It intersects with the new railway in Três Lagoas (MS), near the Rio Branco (MS) terminal.

The main waterways were Tapajós, with around 33.4 million tonnes transported between Itaituba (PA) and Santarém (PA) (extension of 251.5 km); Amazonas; with 18.1 million tonnes

between Santatém (PA) and Afuá (PA) (512.1 km); and Tocantins; with over 14.8 million tonnes between Almeirim (PA) and Barcarena (PA) and Belém (PA) (459.1 km).

In the road network, the stretches that transported the highest volumes are small and are located around exporting ports or the main producing areas. The 31.8 km road stretch around the port of Santos transported more than 58.5 million tonnes; the 28.3 km stretch around the port of Paranaguá carried between 28.1 and 34.8 million tonnes; the 130.8 km between Sorriso (MT) and Sinop (MT) transported between 20.9 and 39.3 million tonnes; and the 19.2 km stretch near the port of Itaituba (PA) received 33.4 million tonnes.

The imported volume by product, month, and entry point in scenario 28 were the same as in scenario 18.

To better assess the impact of the new railway, a scenario with the 2035 transportation network and reduced railway freight cost, unconstrained static storage capacity, and weights $\alpha=1$ and $\beta=15$ was executed. The addition of the new railway decreased the total TKU in 1.8%, the total costs in 0.1% (R\$ 839.5 million), the total CO₂ emissions in 1.1%, the maximum stored volume in 0.2%, and the total increase in static storage in 2.6%; and increased the volume transported by railways in 2.9 million tonnes. The lower railway freight cost led to higher usage of the railway network, and the addition of the new railway generated a shift of volume among the railways, attracting only 2.9 million tonnes of new cargo, but generating a positive impact in reducing costs and emissions. Considering only the domestic market flows (*od*, *oe*, and *id*), there was a reduction of 0.4% in total costs (R\$ 972.3 million) and of 1.8% in CO₂ emissions. Thus, the new railway had a greater positive impact in the domestic market flows and improved the Brazilian logistics network for the domestic market of agricultural products in a more sustainable way.

5.3. Comparison of the transportation matrix

Using Table 1 as reference, the improved Brazilian transportation matrices are compared to the other relevant countries in Table 31. Scenario 3 from the first level and scenario 18 from the second level were selected, since they presented the best solutions, and scenario 5 from the second level was chosen as reference. Scenario 8 from the second level was selected to illustrate the impact of considering both the minimal cost and the CO₂ emissions in the objective function.

Scenario 3 of the first level used a reduced version of the PNL-2035 Brazilian O-D cargo matrix total volume, while scenarios 5, 8 and 18 of the second level utilized the estimated 2035 volumes for maize, soybean, and soybean meal.

Table 31. Modal split of freight transportation (as of 2019, %TKU or %TKM) in different countries and estimated for Brazil in 2035.

Country	Modal split of freight transportation		
	Road	Railway	Waterway/Cabotage
Russia	9%	87%	3%
Canada	32%	57%	12%
Australia	28%	57%	15%
China	36%	14%	49%
United States	55%	35%	10%
European Union	52%	11%	37%
Brazil 2019	64%	22%	15%
Brazil 2035 (First level - scenario 3)	40%	42%	19%
Brazil 2035 (Second level - scenario 5)	57%	23%	20%
Brazil 2035 (Second level - scenario 8)	51%	33%	16%
Brazil 2035 (Second level - scenario 18)	38%	40%	22%

Sources: CNT (2018); European Commission (2021a); ILOS (2020); Rodrigue (2020); Stapran (2018), and the results from this thesis.

The improved Brazilian transportation matrices of the scenarios 3 and 18 were very similar and were more balanced and more comparable to the other countries than the current situation (scenario 5). The addition of the new railway and the optimal increase in static storage capacity considering only the minimization of total cost (scenario 8) led to results more alike the current situation (scenario 5) than when including the CO₂ emissions in the objective function (scenario 18). Thus, the expected 2035 multimodal network can lead to a slightly more balanced transportation matrix, but better results will be achieved with the addition of other projects, such as a new railway connecting the domestic markets of the Center-West and South regions, increase in the static storage capacity of bulk warehouses, and incentives and measures towards the reduction of CO₂ emissions.

6. CONCLUSION

In the past few decades, the Brazilian transportation matrix has been dominated by the road mode, especially in the transportation of agricultural products to the domestic markets, where the other modes have an almost null participation. This situation is harmful in both economic and environmental dimensions, as millions of tonnes in goods are transported by trucks over 2,000 km.

Thus, this thesis aimed to improve the Brazilian logistics network for the domestic market of agricultural products in a more sustainable way by proposing a two-level optimization model for transportation and warehouse networks integrated with a Geographic Information Systems (GIS). The first level is a railway network design model that projects a new railway connecting the Center-West and South regions, selecting the start, intermediate, and end terminals within the area of influence and the potential cargo criteria and that maximizes the cost-benefit ratio. The second level is a GIS-based optimization model for transportation and warehouse networks that minimizes the total cost and CO₂ emissions of the maize, soybean, and soybean meal Brazilian supply.

The new railway was included in the 2035 Brazilian multimodal transportation network and it was possible to assess its performance against the other infrastructures. The proposed new railway generated positive results, attracting substantial cargo volume and generating a more balanced and rational transportation matrix. The positive effects increased when the new railway was combined with an optimal increase of the static storage capacity of the bulk warehouses. It was possible to conclude that it is worth having a railway linking the Center-West and South regions with the selected terminals and design.

Although the second level model is a classic transportation model, the addition of warehouses, monthly period, CO₂ emissions, and GIS generated more complete solutions and detailed results.

The use of GIS enabled the identification of the main logistic infrastructures used in the transportation of products and the calculation of the transportation matrix. Then, it was possible to compare the improved Brazilian transportation matrix with other countries of comparable size, which can subsidize policy makers in their decisions.

On the other hand, the literature review on other countries' historical background, current logistics infrastructure, and path towards a more balanced and sustainable modal split of freight transportation reinforces the need of multiple and coordinated actions and measures, and of a long-term planning strategy.

Therefore, this thesis achieved its research objectives and proved its research hypotheses. To the best of the author's knowledge, this is the first study to propose a railway network design

model that automatically chooses the links and terminals of a new railway. Other papers did the selection manually (Isler et al., 2021), only selected the links (Maia and Couto, 2013) or selected projects (Alireza Seyedvakili et al., 2020; Yamada et al., 2009; Yamada and Febri, 2015).

It is important to highlight that this is a strategic analysis. The new railway's links and terminals' location are a proposal and can be further improved with railway alignment models. In addition, further versions of the railway network design's constructive heuristic can overlook existent links and terminals, improving the solution's value and its assessment. It would be interesting to use a function to calculate the railway link construction cost, varying with the distance and the declivity (topography), and to consider different classes and types of terminals (Isler et al., 2021). Further analysis could consider constrained capacity in links and terminals, assessing traffic and congestion. A sensitivity analysis can be performed, running scenarios 1 to 4 with the microregion classification to build the used O-D matrix; executing scenarios 5 to 10 with a discounted freight rate for railways and waterways to see if there is a change in the area of influence; testing scenarios with only the traversed states as the area of influence; changing the O-D cargo matrix criteria so that all cargo volume is considered, but with less granularity; and using an all-or-nothing flow assignment technique, instead of the deterministic rule, allocating 100% of the transported volume to the most economical transportation mode.

In the second level model, future studies can include the warehouses' drying capacity, that is especially important in Rio Grande do Sul, and add other products, such as ethanol, sugar cane, and fertilizers.

Other improvements include automatization of data outputs and data inputs from the first level to the second level and vice versa; improve the GIS data manipulation so it is easier and more automated; execute both levels iteratively, until no further significative improvement is achieved; and include in the expected railway network the full version of the Nova Ferroeste (with the stretches Dourados (MS) to Maracaju (MS), Cascavel (PR) to Foz do Iguaçu (PR), Cascavel to Chapecó (SC), and Guarapuava (PR) to port of Paranaguá (PR)) and new projects from the Railway Authorization Program.

Despite the high number of additional improvements, the proposed two-level optimization model generated a new railway that runs close to important producing and consuming centers, undermining the political influence in the decisions regarding railway design.

With the Railway Authorization Program, it is expected that the number of railways in Brazil will significantly increase. Thus, this thesis can aid policy makers and railway designers in building railways that will actually contribute to improve the Brazilian logistics network for the domestic market of agricultural products in a more sustainable way.

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APPENDICES

APPENDIX A. Code for the constructive heuristic of the railway network design model.

```

import arcpy
import datetime
import sys
import arcpy_functions

# Store start time
now = datetime.datetime.now()

# Use parallel processing (let each tool determine how many processes to use)
arcpy.env.parallelProcessingFactor = ""

##### Preparing environment and data
# Set environment
arcpy.env.workspace = "C:/Users/conni/Documents/Tese/Workspace"
arcpy.env.overwriteOutput = "TRUE"
arcpy.CheckOutExtension("Network")

# Set names for input files (flows and origins/destinations)
flow_feature = "C:/Users/conni/Documents/Tese/Tese.gdb/matriz_OD_2035"
origins = "C:/Users/conni/Documents/Tese/Tese.gdb/Center_Municipios"
international_origins = "C:/Users/conni/Documents/Tese/Tese.gdb/PNL2017_OD_Inter"
bolivia_origin = "C:/Users/conni/Documents/Tese/Tese.gdb/OD_Bolivia"

# Create geodatabases
out_gdb_path = "C:/Users/conni/Documents/Tese"
out_gdb_name = "Intermediary_Files"
arcpy.CreateFileGDB_management(out_gdb_path, out_gdb_name)
out_path = out_gdb_path + "/" + out_gdb_name + ".gdb"

best_solution_gdb_name = "Best_Solution"
arcpy.CreateFileGDB_management(out_gdb_path, best_solution_gdb_name)
best_solution_path = out_gdb_path + "/" + best_solution_gdb_name + ".gdb"

# Create feature class for Stops data
out_name = "stops"
geometry_type = "POINT"
arcpy.management.CreateFeatureclass(out_path, out_name, geometry_type, spatial_reference = origins)
arcpy.management.AddField(out_path + "/" + out_name, "LP_ID", "TEXT")
stops = out_path + "/" + out_name

# Use a cursor to obtain information from origins/destinations and insert rows in the Stops feature
# "SHAPE@XY" store the coordinates data of each point in the feature class
with arcpy.da.SearchCursor(origins, ["CD_MUN", "SHAPE@XY"]) as cur_a:
    for row in cur_a:
        cur_b = arcpy.da.InsertCursor(stops, ["LP_ID", "SHAPE@XY"])
        cur_b.insertRow([row[0],row[1]])

with arcpy.da.SearchCursor(international_origins, ["cod_mun", "SHAPE@XY"]) as cur_a:
    for row in cur_a:
        cur_b = arcpy.da.InsertCursor(stops, ["LP_ID", "SHAPE@XY"])
        cur_b.insertRow([row[0],row[1]])

with arcpy.da.SearchCursor(bolivia_origin, ["CD_MUN", "SHAPE@XY"]) as cur_a:
    for row in cur_a:
        cur_b = arcpy.da.InsertCursor(stops, ["LP_ID", "SHAPE@XY"])
        cur_b.insertRow([row[0],row[1]])

```

```

# Delete identical records
arcpy.management.DeleteIdentical(stops, ["LP_ID"])
arcpy.management.AddIndex(stops, ["LP_ID"], "Index2", "UNIQUE", "ASCENDING")

# Create a network dataset layer from a template. The layer will be referenced using its name.
inNetworkDataset = "C:/Users/conni/Documents/Tese/Tese.gdb/Brasil/Brasil_ND"
try:
    arcpy.management.Delete(inNetworkDataset)
except Exception:
    e = sys.exc_info()[1]
    print(e.args[0])

# The ND template includes the 2035 expected Brazilian multimodal transportation network
original_output_xml_file = "C:/Users/conni/Documents/Tese/NDTemplate.xml"
network_location = "C:/Users/conni/Documents/Tese/Tese.gdb/Brasil"

arcpy.na.CreateNetworkDatasetFromTemplate(original_output_xml_file, network_location)
arcpy.na.BuildNetwork(inNetworkDataset)

nd_layer_name = "Brasil"
arcpy.nax.MakeNetworkDatasetLayer(inNetworkDataset, nd_layer_name)

# Get the Road travel mode for the analysis
nd_travel_modes = arcpy.nax.GetTravelModes(nd_layer_name)
travel_mode = nd_travel_modes["Rodo_Marit_Frete"]

# Instantiate a Route solver object
route = arcpy.nax.Route(nd_layer_name)

# Set Route properties
route.travelMode = travel_mode
route.accumulateAttributeNames = ["Frete", "Length", "FreteRodo"]
route.routeShapeType = arcpy.nax.RouteShapeType.NoLine

##### Uploading input data for the route solver
# Using cursor, read each O-D pair and insert the route name, origin, and destination in the Route solver input table
with arcpy.da.UpdateCursor(flow_feature, ["cod_mun_origem", "cod_mun_destino"]) as cur:
    for row in cur:
        try:
            arcpy.management.MakeFeatureLayer(stops, "stops_lyr")

            where_clause_1 = "'LP_ID' = " + str(row[0]) + ""
            arcpy.management.SelectLayerByAttribute('stops_lyr', 'NEW_SELECTION', where_clause_1)

            where_clause_2 = "'LP_ID' = " + str(row[1]) + ""
            arcpy.management.SelectLayerByAttribute('stops_lyr', 'ADD_TO_SELECTION', where_clause_2)

            route_name = str(row[0]) + " - " + str(row[1])

            # Set input Stops using cursor
            fields = ["Name", "RouteName", "SHAPE@XY"]
            with arcpy.da.SearchCursor("stops_lyr", ["LP_ID", "SHAPE@XY"]) as cur_1:
                for row_1 in cur_1:
                    cur_2 = route.insertCursor(arcpy.nax.RouteInputDataType.Stops, fields)
                    cur_2.insertRow([row_1[0], route_name, row_1[1]])
        except Exception:
            e = sys.exc_info()[1]
            print(e.args[0])
            arcpy.AddError(e.args[0])
            cur.updateRow(row)

```

```

##### Route solver - Road transportation mode
# Solve the analysis for Road mode
result = route.solve()

##### Exporting and calculating route solver results - Road mode
# Export results to a feature class
nax_road_routes, nax_road_edges, outtable_road = arcgis_functions.export_calculate_results(best_solution_path,
origins, result, flow_feature)

# Rename the tables with the Road mode results
arcpy.management.Rename(best_solution_path + "/" + "nax_routes_zero", best_solution_path + "/" +
"nax_road_routes")
nax_road_routes = best_solution_path + "/" + "nax_road_routes"
arcpy.management.Rename(best_solution_path + "/" + "nax_edges_zero", best_solution_path + "/" +
"nax_road_edges")
nax_road_edges = best_solution_path + "/" + "nax_road_edges"
arcpy.management.Rename(best_solution_path + "/" + "nax_edges_summary_zero", best_solution_path + "/" +
"nax_road_edges_summary")
outtable_road = best_solution_path + "/" + "nax_road_edges_summary"

# Calculate adjusted road freight (removes additional R$ 10,000 for maritime mode, to avoid maritime mode for
domestic routes)
expression1 = "getAdjustedRoadFreight(!Total_Kilometers!)"
codeblock1 = """
def getAdjustedRoadFreight(freight):
    if freight > 10094:
        return freight-10000
    else:
        return freight """
arcpy.management.CalculateField(nax_road_routes, "road_freight", expression1, "PYTHON3", codeblock1,
field_type="DOUBLE")

# export road mode results to excel file
arcpy.conversion.TableToExcel(nax_road_routes, "nax_road_routes.xlsx")

# store Route solver input for next iterations
arcpy.management.CreateFeatureclass(best_solution_path, "nax_stops_input", "", "", "", "", origins)
nax_stops_input_path = best_solution_path + "/" + "nax_stops_input"
if result.solveSucceeded:
    result.export(arcpy.nax.RouteInputDataType.Stops, nax_stops_input_path)
else:
    print("Solver failed")
    print(result.solverMessages(arcpy.nax.MessageSeverity.All))

##### Route solver - multimodal
# solve Route solver for Multimodal transport mode
travel_mode = nd_travel_modes["Multi_Frete"]
route.travelMode = travel_mode
result = route.solve()

##### Exporting and calculating route solver results - multimodal
# Export results to a feature class
nax_routes_zero, nax_edges_zero, outtable_zero = arcgis_functions.export_calculate_results(best_solution_path,
origins, result, flow_feature)

##### Apply allocation rule and calculate total transport cost for the existing transportation
network
# add road mode freight cost to the multimodal network data
try:

```



```

    arcpy.management.AlterField(nax_routes_zero, "Total_Kilometers", "multi_freight", "multi_freight")
except Exception:
    e = sys.exc_info()[1]
    print(e.args[0])

arcpy.management.JoinField(nax_routes_zero, "Name", nax_road_routes, "Name", ["road_freight"])

# apply allocation rule and calculate total transport cost per route
expression4 = "getAllocationFreight(!vol_total!, !road_freight!, !multi_freight!)"
codeblock4 = """
def getAllocationFreight(volume, roadfreight, multifreight):
    if (1-multifreight/roadfreight > 0.2):
        return volume*(0.1*roadfreight+0.9*multifreight)
    elif((1-(multifreight/roadfreight) > 0.1) and (1-(multifreight/roadfreight) <= 0.2)):
        return volume*(0.2*roadfreight+0.8*multifreight)
    elif((1-(multifreight/roadfreight) > 0.01) and (1-(multifreight/roadfreight) <= 0.1)):
        return volume*(0.3*roadfreight+0.7*multifreight)
    elif((1-(multifreight/roadfreight) > 0.00001) and (1-(multifreight/roadfreight) <= 0.01)):
        return volume*(0.9*roadfreight+0.1*multifreight)
    else:
        return volume*roadfreight """
arcpy.management.CalculateField(nax_routes_zero, "allocation_freight", expression4, "PYTHON3", codeblock4,
field_type="DOUBLE")

# calculate total transport cost for the existing transportation network - per solution
nax_routes_summary_zero = arcpy.management.CreateTable(best_solution_path, "nax_routes_summary_zero")
arcpy.analysis.Statistics(nax_routes_zero, nax_routes_summary_zero, [{"allocation_freight", "SUM"}, {"vol_total",
"SUM"}])

total_freight_cost_zero = [row[0]for row in arcpy.da.SearchCursor(nax_routes_summary_zero,
["SUM_allocation_freight"])]

# export multimodal zero results to excel file
nax_routes_zero = best_solution_path + "/" + "nax_routes_zero"
nax_routes_summary_zero = best_solution_path + "/" + "nax_routes_summary_zero"
arcpy.conversion.TableToExcel([nax_routes_zero, nax_routes_summary_zero], "nax_routes_zero.xlsx")

# Create network dataset with new railway edges and terminals and run Route Solver
try:
    arcpy.management.Delete(inNetworkDataset)
except Exception:
    e = sys.exc_info()[1]
    print(e.args[0])

new_output_xml_file = "C:/Users/conni/Documents/Tese/NDTemplate_Delaunay.xml"

arcpy.na.CreateNetworkDatasetFromTemplate(new_output_xml_file, network_location)
arcpy.na.BuildNetwork(inNetworkDataset)
arcpy.nax.MakeNetworkDatasetLayer(inNetworkDataset, nd_layer_name)

# Instantiate a Route solver object.
route = arcpy.nax.Route(nd_layer_name)

# Set Route properties
route.travelMode = travel_mode
route.accumulateAttributeNames = ["Frete", "Length", "FreteRodo"]
route.routeShapeType = arcpy.nax.RouteShapeType.NoLine
""" routeShapeType: NoLine (No route shapes will be returned, faster processing) """

# Load inputs
route.load(arcpy.nax.RouteInputDataType.Stops, nax_stops_input_path)

```

```

# Solve the analysis
result = route.solve()

# Parameters
new_rail_edges = "Ferro_Novo"
new_rail_terminals = "Suporte_Pontos_FerroNovo"
new_rail_edges_path = "C:/Users/conni/Documents/Tese/Tese.gdb/Ferro_Novo"
new_rail_terminals_path = "C:/Users/conni/Documents/Tese/Tese.gdb/Suporte_Pontos_FerroNovo"

open_terminal_cost = float(34500000)
building_unit_cost = float(25200000)
minimum_edge_volume = float(3500000)

# support - expression - summarize used junctions, find if there is one or more new railways (used in function
export_calculate_multimodal_results)
expression2 = "getOneRailwayCheck(!FREQUENCY)"
codeblock2 = ""
def getOneRailwayCheck(freq):
    if freq <= 2:
        return "1"
    else:
        return "+1" ""

selected_edges = {}
solution = 0

# call function export_calculate_multimodal_results
solution_value, junctions_volume, tab_custo_frete_total, tab_junctions_route, used_new_rail_edges, outtable,
nax_routes_path, nax_edges_path = arcgis_functions.export_calculate_multimodal_results(out_path, origins, result,
new_rail_terminals, new_rail_edges, open_terminal_cost, building_unit_cost, expression2, codeblock2,
nax_road_routes, total_freight_cost_zero, expression4, codeblock4, expression5, codeblock5)

##### Store first solution
best_solution_value = solution_value
solution = 0
selected_edges[solution] = []

# save initial solution
with arcpy.da.SearchCursor(used_new_rail_edges, ["SourceOID"]) as cur_11:
    for row_11 in cur_11:
        selected_edges[solution].append(row_11[0])

# save used edges - only domestic routes
number_rows_value = int(len(selected_edges[solution]))

Type = "Domestic"
used_new_rail_edges_initial = arcpy.management.CreateTable(out_path, "used_new_rail_edges_initial")
where_clause_2 = "RouteType" + " = " + Type + ""
temp_select2 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges, 'NEW_SELECTION',
where_clause_2)
arcpy.management.CopyRows(temp_select2, used_new_rail_edges_initial)

# sort used edges by volume - descending
used_new_rail_edges_sort = arcpy.management.CreateTable(out_path, "used_new_rail_edges_sort")
arcpy.management.Sort(used_new_rail_edges_initial, used_new_rail_edges_sort, [!SUM_vol_total",
"DESCENDING"])
arcpy.management.CalculateField(used_new_rail_edges_sort, "ObjectID_Num", "!ObjectID!", field_type="LONG")

# add initial volume info to new railway edges
arcpy.management.AddIndex(used_new_rail_edges_sort, ["SourceOID"], "Index4", "UNIQUE", "ASCENDING")
try:
    arcpy.management.AddIndex(new_rail_edges_path, ["ID"], "Index4", "UNIQUE", "ASCENDING")

```

```

    arcpy.management.JoinField(new_rail_edges_path, "ID", used_new_rail_edges_sort, "SourceOID",
["SUM_vol_total", "ObjectID_Num"])
    where_clause_3 = "SUM_vol_total" is null'
    temp_select3 = arcpy.management.SelectLayerByAttribute(new_rail_edges_path, 'NEW_SELECTION',
where_clause_3)
    arcpy.management.CalculateField(temp_select3, "SUM_vol_total", 0)
    arcpy.management.SelectLayerByAttribute(new_rail_edges_path, 'CLEAR_SELECTION')
except Exception:
    e = sys.exc_info()[1]
    print(e.args[0])

# add start and end terminals info to sorted used railway edges
arcpy.management.JoinField(used_new_rail_edges_sort, "SourceOID", new_rail_edges_path, "ID", ["StartPtID",
"EndPtID", "UF"])

# find used edges by start and end terminals - group (edges were split due to topology)
used_new_rail_edges_initial_group = arcpy.management.CreateTable(out_path,
"used_new_rail_edges_initial_group")
statsFields2 = [["ObjectID_Num", "MIN"]]
casefield2 = ["StartPtID", "EndPtID", "UF"]
arcpy.analysis.Statistics(used_new_rail_edges_sort, used_new_rail_edges_initial_group, statsFields2, casefield2)

# sort used edges by volume - descending - with start and end terminals info
used_new_rail_edges_initial_group_sort = arcpy.management.CreateTable(out_path,
"used_new_rail_edges_initial_group_sort")
arcpy.management.Sort(used_new_rail_edges_initial_group, used_new_rail_edges_initial_group_sort,
[["MIN_ObjectID_Num", "ASCENDING"]])
arcpy.management.CalculateField(used_new_rail_edges_initial_group_sort, "ObjectID_Num", "!ObjectID!",
field_type="LONG")

# calculate edges order by state
countPR=0
countSC=0
countRS=0
countMS=0
countOthers=0

arcpy.management.CalculateField(used_new_rail_edges_initial_group_sort, "Edges_Order", 0,
field_type="SHORT")
with arcpy.da.UpdateCursor(used_new_rail_edges_initial_group_sort,["UF", "Edges_Order"]) as cur_13:
    for row_13 in cur_13:
        if(row_13[0] == '41'):
            countPR += 1
            row_13[1] = countPR
        elif(row_13[0] == '42'):
            countSC += 1
            row_13[1] = countSC
        elif(row_13[0] == '43'):
            countRS += 1
            row_13[1] = countRS
        elif(row_13[0] == '50'):
            countMS += 1
            row_13[1] = countMS
        else:
            countOthers += 1
            row_13[1] = countOthers
    cur_13.updateRow(row_13)

# save solution's transversed edges per OD pair, total freight cost and TKU, new terminals by OD pair, volume by
new terminal
arcpy.conversion.TableToGeodatabase([outtable, nax_routes_path, tab_custo_frete_total, tab_junctions_route,
junctions_volume, used_new_rail_edges], best_solution_path)

```

```

# store used_new_rail_edges in best_solution_path to run remove local search in the end
used_new_rail_edges_store = arcpy.management.CreateTable(best_solution_path, "used_new_rail_edges_store")
where_clause_2 = "SourceOID" is not null'
temp_select2 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges, 'NEW_SELECTION',
where_clause_2)
arcpy.management.CopyRows(temp_select2, used_new_rail_edges_store)
arcpy.management.Rename(best_solution_path + "/" + "used_new_rail_edges_store", best_solution_path + "/" +
"used_new_rail_edges" + str(len(selected_edges)-1))

# create table with solution number and solution value
solution_info = arcpy.management.CreateTable(best_solution_path, "solution_info")
arcpy.management.AddField(solution_info, "Solution_Nb", "LONG")
arcpy.management.AddField(solution_info, "Solution_value", "DOUBLE")

fields = ['Solution_Nb', 'Solution_value']
cursor = arcpy.da.InsertCursor(solution_info, fields)
cursor.insertRow((len(selected_edges)-1, solution_value))
del cursor

##### Executing scenarios and local search
new_network_location = "C:/Users/conni/Documents/Tese/Heuristic.gdb/Brasil"
NewNetworkDataset = "C:/Users/conni/Documents/Tese/Heuristic.gdb/Brasil/Brasil_ND"

number_scenarios = 7
highest_volume_edge = [[1, 0.005], [2, 0.010], [3, 0.015], [4, 0.020], [5, 0.025], [6, 0.030], [7, 0.035]]
test9 = 0
test8 = 0
test7 = 0
test6 = 0
test5 = 0
test4 = 0
test3 = 0
test2 = 0
test1 = 0
best_selected_rail_edges = best_solution_path + "/" + new_rail_edges
btest9 = 0
btest8 = 0
btest7 = 0
btest6 = 0
btest5 = 0
btest4 = 0
btest3 = 0
btest2 = 0
btest1 = 0

for j in range(2, 6, 1):
    # prepare new network dataset
    try:
        arcpy.management.Delete(NewNetworkDataset)
        arcpy.management.Delete(new_network_location + "/" + new_rail_edges)
    except Exception:
        e = sys.exc_info()[1]
        print(e.args[0])

    lower_bound, selected_rail_edges = arcgis_functions.prepare_network_dataset(new_rail_edges_path,
new_network_location, new_rail_edges, selected_edges, len(selected_edges), j,
used_new_rail_edges_initial_group_sort)

    # break "for" if selected_edges[solution] was already used, only for local search
    repeat = 0

```

```

current_solution = len(selected_edges)-1
if(repeat==0):
    # create new network dataset
    arcpy.na.CreateNetworkDatasetFromTemplate(new_output_xml_file, new_network_location)
    arcpy.na.BuildNetwork(NewNetworkDataset)
    arcpy.nax.MakeNetworkDatasetLayer(NewNetworkDataset, nd_layer_name)

##### Finding a new multimodal solution
# Instantiate a Route solver object.
route = arcpy.nax.Route(nd_layer_name)

# Set Route properties
route.travelMode = travel_mode
route.accumulateAttributeNames = ["Frete", "Length", "FreteRodo"]
route.routeShapeType = arcpy.nax.RouteShapeType.NoLine

# Load inputs
route.load(arcpy.nax.RouteInputDataType.Stops, nax_stops_input_path)

# Solve the analysis
result = route.solve()

# call function export_calculate_multimodal_results
solution_value, junctions_volume, tab_custo_frete_total, tab_junctions_route, used_new_rail_edges, outtable,
nax_routes_path, nax_edges_path = arcgis_functions.export_calculate_multimodal_results(out_path, origins, result,
new_rail_terminals, new_rail_edges, open_terminal_cost, building_unit_cost, expression2, codeblock2,
nax_road_routes, total_freight_cost_zero, expression4, codeblock4, expression5, codeblock5)

# store used_new_rail_edges in best_solution_path to run remove local search in the end
used_new_rail_edges_store = arcpy.management.CreateTable(best_solution_path,
"used_new_rail_edges_store")
where_clause_2 = "'SourceOID' is not null"
temp_select2 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges, 'NEW_SELECTION',
where_clause_2)
arcpy.management.CopyRows(temp_select2, used_new_rail_edges_store)
arcpy.management.Rename(best_solution_path + "/" + "used_new_rail_edges_store", best_solution_path +
"/" + "used_new_rail_edges" + str(len(selected_edges)-1))

fields = ['Solution_Nb', 'Solution_value']
cursor = arcpy.da.InsertCursor(solution_info, fields)
cursor.insertRow((len(selected_edges)-1, solution_value))
del cursor

##### Store best solution
if (solution_value > best_solution_value):
    best_solution_value = solution_value
    best_solution_iteration = j
    best_solution_position = len(selected_edges)

# save solution's transversed edges per OD pair, total freight cost and TKU, new terminals by OD pair,
volume by new terminal
arcpy.conversion.TableToGeodatabase([outtable, nax_routes_path, tab_custo_frete_total,
tab_junctions_route, junctions_volume, used_new_rail_edges], best_solution_path)
nax_edges_path = out_path + "/" + "nax_edges"
arcpy.conversion.FeatureClassToGeodatabase(nax_edges_path, best_solution_path)

selected_rail_edges_store = arcpy.management.CreateTable(best_solution_path, "selected_rail_edges_store")
where_clause_2 = "'ID' is not null"
temp_select2 = arcpy.management.SelectLayerByAttribute(selected_rail_edges, 'NEW_SELECTION',
where_clause_2)
arcpy.management.CopyRows(temp_select2, selected_rail_edges_store)

```

```

##### Local search procedure
for m in range(0,4,1):
    try:
        arcpy.management.Delete(NewNetworkDataset)
    except Exception:
        e = sys.exc_info()[1]
        print(e.args[0])

    test9, test8, test7, test6, test5, test4, test3, test2, test1 = arcgis_functions.local_search(out_path,
new_rail_edges_path, selected_rail_edges, new_rail_edges, new_network_location, m, selected_edges,
used_new_rail_edges, test9, test8, test7, test6, test5, test4, test3, test2, test1, minimum_edge_volume, lower_bound)

    # break "for" if selected_edges[solution] was already used
    repeat = 0
    current_solution = len(selected_edges)-1
    for k in range(0, current_solution, 1):
        if(selected_edges[k] == selected_edges[current_solution]):
            repeat = 1
    if(repeat==0):
        arcpy.na.CreateNetworkDatasetFromTemplate(new_output_xml_file, new_network_location)
        arcpy.na.BuildNetwork(NewNetworkDataset)
        arcpy.nax.MakeNetworkDatasetLayer(NewNetworkDataset, nd_layer_name)

        ##### Finding a new multimodal solution
        # Instantiate a Route solver object.
        route = arcpy.nax.Route(nd_layer_name)

        # Set Route properties
        route.travelMode = travel_mode
        route.accumulateAttributeNames = ["Frete", "Length", "FreteRodo"]
        route.routeShapeType = arcpy.nax.RouteShapeType.NoLine

        # Load inputs
        route.load(arcpy.nax.RouteInputDataType.Stops, nax_stops_input_path)

        # Solve the analysis
        result = route.solve()

        # call function export_calculate_multimodal_results
        solution_value, junctions_volume, tab_custo_frete_total, tab_junctions_route, used_new_rail_edges,
outtable, nax_routes_path, nax_edges_path = arcgis_functions.export_calculate_multimodal_results(out_path,
origins, result, new_rail_terminals, new_rail_edges, open_terminal_cost, building_unit_cost, expression2,
codeblock2, nax_road_routes, total_freight_cost_zero, expression4, codeblock4, expression5, codeblock5)

        # store used_new_rail_edges in best_solution_path to run remove local search in the end
        used_new_rail_edges_store = arcpy.management.CreateTable(best_solution_path,
"used_new_rail_edges_store")
        where_clause_2 = "SourceOID" is not null'
        temp_select2 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges, 'NEW_SELECTION',
where_clause_2)
        arcpy.management.CopyRows(temp_select2, used_new_rail_edges_store)
        arcpy.management.Rename(best_solution_path + "/" + "used_new_rail_edges_store", best_solution_path
+ "/" + "used_new_rail_edges" + str(len(selected_edges)-1))

        fields = ['Solution_Nb', 'Solution_value']
        cursor = arcpy.da.InsertCursor(solution_info, fields)
        cursor.insertRow((len(selected_edges)-1, solution_value))
        del cursor

        ##### Store best solution
        if (solution_value > best_solution_value):
            best_solution_value = solution_value

```

```

        best_solution_iteration = j
        best_solution_position = len(selected_edges)

        # save solution's transversed edges per OD pair, total freight cost and TKU, new terminals by OD pair,
        volume by new terminal
        arcpy.conversion.TableToGeodatabase([outtable, nax_routes_path, tab_custo_frete_total,
tab_junctions_route, junctions_volume, used_new_rail_edges], best_solution_path)
        nax_edges_path = out_path + "/" + "nax_edges"
        arcpy.conversion.FeatureClassToGeodatabase(nax_edges_path, best_solution_path)

        selected_rail_edges_store = arcpy.management.CreateTable(best_solution_path,
"selected_rail_edges_store")
        where_clause_2 = "ID" is not null
        temp_select2 = arcpy.management.SelectLayerByAttribute(selected_rail_edges, 'NEW_SELECTION',
where_clause_2)
        arcpy.management.CopyRows(temp_select2, selected_rail_edges_store)

# run remove local search
with arcpy.da.SearchCursor(solution_info, ["Solution_Nb", "OBJECTID"]) as cur_12:
    for row_12 in cur_12:
        try:
            arcpy.management.Delete(NewNetworkDataset)
        except Exception:
            e = sys.exc_info()[1]
            print(e.args[0])

        used_new_rail_edges = best_solution_path + "/" + "used_new_rail_edges" + str(row_12[0])
        arcgis_functions.local_search_remove(out_path, new_rail_edges_path, selected_rail_edges, new_rail_edges,
new_network_location, selected_edges, used_new_rail_edges, minimum_edge_volume)

        # break "for" if selected_edges[solution] was already used
        repeat = 0
        current_solution = len(selected_edges)-1
        for k in range(0, current_solution, 1):
            if(selected_edges[k] == selected_edges[current_solution]):
                repeat = 1
        if(repeat==0):
            arcpy.na.CreateNetworkDatasetFromTemplate(new_output_xml_file, new_network_location)
            arcpy.na.BuildNetwork(NewNetworkDataset)
            arcpy.nax.MakeNetworkDatasetLayer(NewNetworkDataset, nd_layer_name)

##### Finding a new multimodal solution
# Instantiate a Route solver object.
route = arcpy.nax.Route(nd_layer_name)

# Set Route properties
route.travelMode = travel_mode
route.accumulateAttributeNames = ["Frete", "Length", "FreteRodo"]
route.routeShapeType = arcpy.nax.RouteShapeType.NoLine

# Load inputs
route.load(arcpy.nax.RouteInputDataType.Stops, nax_stops_input_path)

# Solve the analysis
result = route.solve()

# call function export_calculate_multimodal_results
solution_value, junctions_volume, tab_custo_frete_total, tab_junctions_route, used_new_rail_edges,
outtable, nax_routes_path, nax_edges_path = arcgis_functions.export_calculate_multimodal_results(out_path,
origins, result, new_rail_terminals, new_rail_edges, open_terminal_cost, building_unit_cost, expression2,
codeblock2, nax_road_routes, total_freight_cost_zero, expression4, codeblock4, expression5, codeblock5)

```

```

# store used_new_rail_edges in best_solution_path to run remove local search in the end
used_new_rail_edges_store = arcpy.management.CreateTable(best_solution_path,
"used_new_rail_edges_store")
where_clause_2 = "SourceOID" is not null
temp_select2 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges, 'NEW_SELECTION',
where_clause_2)
arcpy.management.CopyRows(temp_select2, used_new_rail_edges_store)
arcpy.management.Rename(best_solution_path + "/" + "used_new_rail_edges_store", best_solution_path +
"/" + "used_new_rail_edges" + str(len(selected_edges)-1))

fields = ['Solution_Nb', 'Solution_value']
cursor = arcpy.da.InsertCursor(solution_info, fields)
cursor.insertRow((len(selected_edges)-1, solution_value))
del cursor

##### Store best solution
if (solution_value > best_solution_value):
    best_solution_value = solution_value
    best_solution_iteration = j
    best_solution_position = len(selected_edges)

# save solution's transversed edges per OD pair, total freight cost and TKU, new terminals by OD pair,
volume by new terminal
arcpy.conversion.TableToGeodatabase([outtable, nax_routes_path, tab_custo_frete_total,
tab_junctions_route, junctions_volume, used_new_rail_edges], best_solution_path)
nax_edges_path = out_path + "/" + "nax_edges"
arcpy.conversion.FeatureClassToGeodatabase(nax_edges_path, best_solution_path)

selected_rail_edges_store = arcpy.management.CreateTable(best_solution_path,
"selected_rail_edges_store")
where_clause_2 = "ID" is not null
temp_select2 = arcpy.management.SelectLayerByAttribute(selected_rail_edges, 'NEW_SELECTION',
where_clause_2)
arcpy.management.CopyRows(temp_select2, selected_rail_edges_store)

number_removed_orig = arcpy.management.GetCount(solution_info)
number_removed = int(number_removed_orig[0]) - 1

# run local search around 5 best solutions

# find 5 best solutions
arcpy.management.CalculateField(solution_info, "ObjectID_Num", "!ObjectID!", field_type="LONG")
solution_info_max = arcpy.management.CreateTable(best_solution_path, "solution_info_max")
statsFields2 = [{"Solution_Nb", "MIN"}]
casefield2 = ["Solution_value"]
arcpy.analysis.Statistics(solution_info, solution_info_max, statsFields2, casefield2)

solution_info_sort = arcpy.management.CreateTable(best_solution_path, "solution_info_sort")
arcpy.management.Sort(solution_info, solution_info_sort, [{"Solution_value", "DESCENDING"}])
arcpy.management.CalculateField(solution_info_sort, "ObjectID_Num", "!ObjectID!", field_type="LONG")

arcpy.management.CalculateField(solution_info_sort, "Keep", 0, field_type="SHORT")

with arcpy.da.UpdateCursor(solution_info_sort, ["Solution_Nb", "Keep", "Solution_value"]) as cur_13:
    for row_13 in cur_13:
        with arcpy.da.SearchCursor(solution_info_max, ["MIN_Solution_Nb", "Solution_value"]) as cur_12:
            for row_12 in cur_12:
                if(row_13[2] == row_12[1] and row_13[0] == row_12[0]):
                    row_13[1] = 1
                    cur_13.updateRow(row_13)
                    break

```



```

where_clause_4 = "Keep" = 0'
temp_select4 = arcpy.management.SelectLayerByAttribute(solution_info_sort, 'NEW_SELECTION',
where_clause_4)
arcpy.management.DeleteRows(temp_select4)

where_clause_4 = "ObjectID_Num" > 5'
temp_select4 = arcpy.management.SelectLayerByAttribute(solution_info_sort, 'NEW_SELECTION',
where_clause_4)
arcpy.management.DeleteRows(temp_select4)

with arcpy.da.SearchCursor(solution_info_sort, ["Solution_Nb", "ObjectID_Num"]) as cur_12:
    for row_12 in cur_12:
        for o in range(0,4,1):
            try:
                arcpy.management.Delete(NewNetworkDataset)
            except Exception:
                e = sys.exc_info()[1]
                print(e.args[0])

            used_new_rail_edges = best_solution_path + "/" + "used_new_rail_edges" + str(row_12[0])
            test9, test8, test7, test6, test5, test4, test3, test2, test1 = arcgis_functions.local_search_top5(out_path,
new_rail_edges_path, selected_rail_edges, new_rail_edges, new_network_location, o, selected_edges,
used_new_rail_edges, test9, test8, test7, test6, test5, test4, test3, test2, test1, minimum_edge_volume, lower_bound,
row_12[0])

            # break "for" if selected_edges[solution] was already used
            repeat = 0
            current_solution = len(selected_edges)-1
            for k in range(0, current_solution, 1):
                if(selected_edges[k] == selected_edges[current_solution]):
                    repeat = 1
            if(repeat==0):
                arcpy.na.CreateNetworkDatasetFromTemplate(new_output_xml_file, new_network_location)
                arcpy.na.BuildNetwork(NewNetworkDataset)
                arcpy.nax.MakeNetworkDatasetLayer(NewNetworkDataset, nd_layer_name)

                ##### Finding a new multimodal solution
                # Instantiate a Route solver object.
                route = arcpy.nax.Route(nd_layer_name)

                # Set Route properties
                route.travelMode = travel_mode
                route.accumulateAttributeName = ["Frete", "Length", "FreteRodo"]
                route.routeShapeType = arcpy.nax.RouteShapeType.NoLine

                # Load inputs
                route.load(arcpy.nax.RouteInputDataType.Stops, nax_stops_input_path)

                # Solve the analysis
                result = route.solve()

                # call function export_calculate_multimodal_results
                solution_value, junctions_volume, tab_custo_frete_total, tab_junctions_route, used_new_rail_edges,
outtable, nax_routes_path, nax_edges_path = arcgis_functions.export_calculate_multimodal_results(out_path,
origins, result, new_rail_terminals, new_rail_edges, open_terminal_cost, building_unit_cost, expression2,
codeblock2, nax_road_routes, total_freight_cost_zero, expression4, codeblock4, expression5, codeblock5)

                # store used_new_rail_edges in best_solution_path to run remove local search in the end
                used_new_rail_edges_store = arcpy.management.CreateTable(best_solution_path,
"used_new_rail_edges_store")
                where_clause_2 = "SourceOID" is not null'

```

```

temp_select2 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges, 'NEW_SELECTION',
where_clause_2)
arcpy.management.CopyRows(temp_select2, used_new_rail_edges_store)
arcpy.management.Rename(best_solution_path + "/" + "used_new_rail_edges_store", best_solution_path
+ "/" + "used_new_rail_edges" + str(len(selected_edges)-1))

fields = ['Solution_Nb', 'Solution_value']
cursor = arcpy.da.InsertCursor(solution_info, fields)
cursor.insertRow((len(selected_edges)-1, solution_value))
del cursor

##### Store best solution
if (solution_value > best_solution_value):
    best_solution_value = solution_value
    best_solution_iteration = j
    best_solution_position = len(selected_edges)

# save solution's transversed edges per OD pair, total freight cost and TKU, new terminals by OD pair,
volume by new terminal
arcpy.conversion.TableToGeodatabase([outtable, nax_routes_path, tab_custo_frete_total,
tab_junctions_route, junctions_volume, used_new_rail_edges], best_solution_path)
nax_edges_path = out_path + "/" + "nax_edges"
arcpy.conversion.FeatureClassToGeodatabase(nax_edges_path, best_solution_path)

selected_rail_edges_store = arcpy.management.CreateTable(best_solution_path,
"selected_rail_edges_store")
where_clause_2 = "ID" is not null'
temp_select2 = arcpy.management.SelectLayerByAttribute(selected_rail_edges, 'NEW_SELECTION',
where_clause_2)
arcpy.management.CopyRows(temp_select2, selected_rail_edges_store)

# run local search - best solution
for o in range(0,4,1):
    try:
        arcpy.management.Delete(NewNetworkDataset)
    except Exception:
        e = sys.exc_info()[1]
        print(e.args[0])

btest9, btest8, btest7, btest6, btest5, btest4, btest3, btest2, btest1 =
arccis_functions.local_search_best(best_selected_rail_edges, best_solution_path, out_path, new_rail_edges_path,
selected_rail_edges, new_rail_edges, new_network_location, o, selected_edges, used_new_rail_edges, btest9, btest8,
btest7, btest6, btest5, btest4, btest3, btest2, btest1, minimum_edge_volume, lower_bound)

# break "for" if selected_edges[solution] was already used
repeat = 0
current_solution = len(selected_edges)-1
for k in range(0, current_solution, 1):
    if(selected_edges[k] == selected_edges[current_solution]):
        repeat = 1
if(repeat==0):
    arcpy.na.CreateNetworkDatasetFromTemplate(new_output_xml_file, new_network_location)
    arcpy.na.BuildNetwork(NewNetworkDataset)
    arcpy.nax.MakeNetworkDatasetLayer(NewNetworkDataset, nd_layer_name)

##### Finding a new multimodal solution
# Instantiate a Route solver object.
route = arcpy.nax.Route(nd_layer_name)

# Set Route properties
route.travelMode = travel_mode
route.accumulateAttributeNames = ["Frete", "Length", "FreteRodo"]

```

```

route.routeShapeType = arcpy.nax.RouteShapeType.NoLine

# Load inputs
route.load(arcpy.nax.RouteInputDataType.Stops, nax_stops_input_path)

# Solve the analysis
result = route.solve()

# call function export_calculate_multimodal_results
solution_value, junctions_volume, tab_custo_frete_total, tab_junctions_route,
used_new_rail_edges, outtable, nax_routes_path, nax_edges_path =
arcpy_functions.export_calculate_multimodal_results(out_path, origins, result, new_rail_terminals, new_rail_edges,
open_terminal_cost, building_unit_cost, expression2, codeblock2, nax_road_routes, total_freight_cost_zero,
expression4, codeblock4, expression5, codeblock5)

# store used_new_rail_edges in best_solution_path to run remove local search in the end
used_new_rail_edges_store = arcpy.management.CreateTable(best_solution_path,
"used_new_rail_edges_store")
where_clause_2 = "SourceOID" is not null'
temp_select2 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges,
'NEW_SELECTION', where_clause_2)
arcpy.management.CopyRows(temp_select2, used_new_rail_edges_store)
arcpy.management.Rename(best_solution_path + "/" + "used_new_rail_edges_store",
best_solution_path + "/" + "used_new_rail_edges" + str(len(selected_edges)-1))

fields = ['Solution_Nb', 'Solution_value']
cursor = arcpy.da.InsertCursor(solution_info, fields)
cursor.insertRow((len(selected_edges)-1, solution_value))
del cursor

##### Store best solution
if (solution_value > best_solution_value):
    best_solution_value = solution_value
    best_solution_iteration = j
    best_solution_position = len(selected_edges)

# save solution's transversed edges per OD pair, total freight cost and TKU, new terminals by
OD pair, volume by new terminal
arcpy.conversion.TableToGeodatabase([outtable, nax_routes_path, tab_custo_frete_total,
tab_junctions_route, junctions_volume, used_new_rail_edges], best_solution_path)
nax_edges_path = out_path + "/" + "nax_edges"
arcpy.conversion.FeatureClassToGeodatabase(nax_edges_path, best_solution_path)

selected_rail_edges_store = arcpy.management.CreateTable(best_solution_path,
"selected_rail_edges_store")
where_clause_2 = "ID" is not null'
temp_select2 = arcpy.management.SelectLayerByAttribute(selected_rail_edges,
'NEW_SELECTION', where_clause_2)
arcpy.management.CopyRows(temp_select2, selected_rail_edges_store)

# run remove local search - after search around top 5
solution_info_store = arcpy.management.CreateTable(best_solution_path, "solution_info_store")
where_clause_2 = "Solution_Nb" is not null'
temp_select2 = arcpy.management.SelectLayerByAttribute(solution_info, 'NEW_SELECTION', where_clause_2)
arcpy.management.CopyRows(temp_select2, solution_info_store)

arcpy.management.CalculateField(solution_info, "ObjectID_Num", '!ObjectID!', field_type="LONG")
where_clause_3 = "ObjectID_Num" + " <=" + str(number_removed)
temp_select3 = arcpy.management.SelectLayerByAttribute(solution_info, 'NEW_SELECTION', where_clause_3)
arcpy.management.DeleteRows(temp_select3)

with arcpy.da.SearchCursor(solution_info, ["Solution_Nb", "OBJECTID"]) as cur_12:

```

```

for row_12 in cur_12:
    try:
        arcpy.management.Delete(NewNetworkDataset)
    except Exception:
        e = sys.exc_info()[1]
        print(e.args[0])

    used_new_rail_edges = best_solution_path + "/" + "used_new_rail_edges" + str(row_12[0])
    arcgis_functions.local_search_remove(out_path, new_rail_edges_path, selected_rail_edges, new_rail_edges,
new_network_location, selected_edges, used_new_rail_edges, minimum_edge_volume)

    # break "for" if selected_edges[solution] was already used
    repeat = 0
    current_solution = len(selected_edges)-1
    for k in range(0, current_solution, 1):
        if(selected_edges[k] == selected_edges[current_solution]):
            repeat = 1
    if(repeat==0):
        arcpy.na.CreateNetworkDatasetFromTemplate(new_output_xml_file, new_network_location)
        arcpy.na.BuildNetwork(NewNetworkDataset)
        arcpy.nax.MakeNetworkDatasetLayer(NewNetworkDataset, nd_layer_name)

        ##### Finding a new multimodal solution
        # Instantiate a Route solver object.
        route = arcpy.nax.Route(nd_layer_name)

        # Set Route properties
        route.travelMode = travel_mode
        route.accumulateAttributeNames = ["Frete", "Length", "FreteRodo"]
        route.routeShapeType = arcpy.nax.RouteShapeType.NoLine

        # Load inputs
        route.load(arcpy.nax.RouteInputDataType.Stops, nax_stops_input_path)

        # Solve the analysis
        result = route.solve()

        # call function export_calculate_multimodal_results
        solution_value, junctions_volume, tab_custo_frete_total, tab_junctions_route, used_new_rail_edges,
outtable, nax_routes_path, nax_edges_path = arcgis_functions.export_calculate_multimodal_results(out_path,
origins, result, new_rail_terminals, new_rail_edges, open_terminal_cost, building_unit_cost, expression2,
codeblock2, nax_road_routes, total_freight_cost_zero, expression4, codeblock4, expression5, codeblock5)

        # store used_new_rail_edges in best_solution_path to run remove local search in the end
        used_new_rail_edges_store = arcpy.management.CreateTable(best_solution_path,
"used_new_rail_edges_store")
        where_clause_2 = "SourceOID" is not null'
        temp_select2 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges, 'NEW_SELECTION',
where_clause_2)
        arcpy.management.CopyRows(temp_select2, used_new_rail_edges_store)
        arcpy.management.Rename(best_solution_path + "/" + "used_new_rail_edges_store", best_solution_path +
"/" + "used_new_rail_edges" + str(len(selected_edges)-1))

        fields = ['Solution_Nb', 'Solution_value']
        cursor = arcpy.da.InsertCursor(solution_info, fields)
        cursor.insertRow((len(selected_edges)-1, solution_value))
        del cursor

        ##### Store best solution
        if (solution_value > best_solution_value):
            best_solution_value = solution_value
            best_solution_iteration = j

```

```

best_solution_position = len(selected_edges)

# save solution's transversed edges per OD pair, total freight cost and TKU, new terminals by OD pair,
volume by new terminal
arcpy.conversion.TableToGeodatabase([outtable, nax_routes_path, tab_custo_frete_total,
tab_junctions_route, junctions_volume, used_new_rail_edges], best_solution_path)
nax_edges_path = out_path + "/" + "nax_edges"
arcpy.conversion.FeatureClassToGeodatabase(nax_edges_path, best_solution_path)

selected_rail_edges_store = arcpy.management.CreateTable(best_solution_path,
"selected_rail_edges_store")
where_clause_2 = "ID" is not null
temp_select2 = arcpy.management.SelectLayerByAttribute(selected_rail_edges, 'NEW_SELECTION',
where_clause_2)
arcpy.management.CopyRows(temp_select2, selected_rail_edges_store)

# run local search - best solution
for o in range(0,4,1):
    try:
        arcpy.management.Delete(NewNetworkDataset)
    except Exception:
        e = sys.exc_info()[1]
        print(e.args[0])

    btest9, btest8, btest7, btest6, btest5, btest4, btest3, btest2, btest1 =
arcpy_functions.local_search_best(best_selected_rail_edges, best_solution_path, out_path, new_rail_edges_path,
selected_rail_edges, new_rail_edges, new_network_location, o, selected_edges, used_new_rail_edges, btest9, btest8,
btest7, btest6, btest5, btest4, btest3, btest2, btest1, minimum_edge_volume, lower_bound)

    # break "for" if selected_edges[solution] was already used
    repeat = 0
    current_solution = len(selected_edges)-1
    for k in range(0, current_solution, 1):
        if(selected_edges[k] == selected_edges[current_solution]):
            repeat = 1
    if(repeat==0):
        arcpy.na.CreateNetworkDatasetFromTemplate(new_output_xml_file, new_network_location)
        arcpy.na.BuildNetwork(NewNetworkDataset)
        arcpy.nax.MakeNetworkDatasetLayer(NewNetworkDataset, nd_layer_name)

        ##### Finding a new multimodal solution
        # Instantiate a Route solver object.
        route = arcpy.nax.Route(nd_layer_name)

        # Set Route properties
        route.travelMode = travel_mode
        route.accumulateAttributeNames = ["Frete", "Length", "FreteRodo"]
        route.routeShapeType = arcpy.nax.RouteShapeType.NoLine

        # Load inputs
        route.load(arcpy.nax.RouteInputDataType.Stops, nax_stops_input_path)

        # Solve the analysis
        result = route.solve()

        # call function export_calculate_multimodal_results
        solution_value, junctions_volume, tab_custo_frete_total, tab_junctions_route, used_new_rail_edges,
outtable, nax_routes_path, nax_edges_path = arcpy_functions.export_calculate_multimodal_results(out_path,
origins, result, new_rail_terminals, new_rail_edges, open_terminal_cost, building_unit_cost, expression2,
codeblock2, nax_road_routes, total_freight_cost_zero, expression4, codeblock4, expression5, codeblock5)

    # store used_new_rail_edges in best_solution_path to run remove local search in the end

```

```

        used_new_rail_edges_store = arcpy.management.CreateTable(best_solution_path,
"used_new_rail_edges_store")
        where_clause_2 = "'SourceOID' is not null"
        temp_select2 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges,
'NEW_SELECTION', where_clause_2)
        arcpy.management.CopyRows(temp_select2, used_new_rail_edges_store)
        arcpy.management.Rename(best_solution_path + "/" + "used_new_rail_edges_store",
best_solution_path + "/" + "used_new_rail_edges" + str(len(selected_edges)-1))

        fields = ['Solution_Nb', 'Solution_value']
        cursor = arcpy.da.InsertCursor(solution_info, fields)
        cursor.insertRow((len(selected_edges)-1, solution_value))
        del cursor

##### Store best solution
if (solution_value > best_solution_value):
    best_solution_value = solution_value
    best_solution_iteration = j
    best_solution_position = len(selected_edges)

# save solution's transversed edges per OD pair, total freight cost and TKU, new terminals by OD
pair, volume by new terminal
arcpy.conversion.TableToGeodatabase([outtable, nax_routes_path, tab_custo_frete_total,
tab_junctions_route, junctions_volume, used_new_rail_edges], best_solution_path)
nax_edges_path = out_path + "/" + "nax_edges"
arcpy.conversion.FeatureClassToGeodatabase(nax_edges_path, best_solution_path)

selected_rail_edges_store = arcpy.management.CreateTable(best_solution_path,
"selected_rail_edges_store")
where_clause_2 = "'ID' is not null"
temp_select2 = arcpy.management.SelectLayerByAttribute(selected_rail_edges,
'NEW_SELECTION', where_clause_2)
arcpy.management.CopyRows(temp_select2, selected_rail_edges_store)

# run final local search - best solution
best_selected_rail_edges = best_solution_path + "/" + "selected_rail_edges_store"
used_new_rail_edges = best_solution_path + "/" + "used_new_rail_edges"

for l in range(0,4,1):
    try:
        arcpy.management.Delete(NewNetworkDataset)
    except Exception:
        e = sys.exc_info()[1]
        print(e.args[0])

    btest9, btest8, btest7, btest6, btest5, btest4, btest3, btest2, btest1 =
arctgis_functions.local_search_best_final(best_selected_rail_edges, best_solution_path, out_path,
new_rail_edges_path, selected_rail_edges, new_rail_edges, new_network_location, l, selected_edges,
used_new_rail_edges, btest9, btest8, btest7, btest6, btest5, btest4, btest3, btest2, btest1, minimum_edge_volume,
lower_bound)

# break "for" if selected_edges[solution] was already used
repeat = 0
current_solution = len(selected_edges)-1
for k in range(0, current_solution, 1):
    if(selected_edges[k] == selected_edges[current_solution]):
        repeat = 1
if(repeat==0):
    arcpy.na.CreateNetworkDatasetFromTemplate(new_output_xml_file, new_network_location)
    arcpy.na.BuildNetwork(NewNetworkDataset)
    arcpy.nax.MakeNetworkDatasetLayer(NewNetworkDataset, nd_layer_name)

```

```

##### Finding a new multimodal solution
# Instantiate a Route solver object.
route = arcpy.nax.Route(nd_layer_name)

# Set Route properties
route.travelMode = travel_mode
route.accumulateAttributeNames = ["Frete", "Length", "FreteRodo"]
route.routeShapeType = arcpy.nax.RouteShapeType.NoLine

# Load inputs
route.load(arcpy.nax.RouteInputDataType.Stops, nax_stops_input_path)

# Solve the analysis
result = route.solve()

# call function export_calculate_multimodal_results
solution_value, junctions_volume, tab_custo_frete_total, tab_junctions_route, used_new_rail_edges, outtable,
nax_routes_path, nax_edges_path = arcgis_functions.export_calculate_multimodal_results(out_path, origins, result,
new_rail_terminals, new_rail_edges, open_terminal_cost, building_unit_cost, expression2, codeblock2,
nax_road_routes, total_freight_cost_zero, expression4, codeblock4, expression5, codeblock5)

# store used_new_rail_edges in best_solution_path to run remove local search in the end
used_new_rail_edges_store = arcpy.management.CreateTable(best_solution_path,
"used_new_rail_edges_store")
where_clause_2 = "'SourceOID' is not null"
temp_select2 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges, 'NEW_SELECTION',
where_clause_2)
arcpy.management.CopyRows(temp_select2, used_new_rail_edges_store)
arcpy.management.Rename(best_solution_path + "/" + "used_new_rail_edges_store", best_solution_path +
"/" + "used_new_rail_edges" + str(len(selected_edges)-1))

count_table = len(used_edges_table)
used_edges_table[count_table] = [len(selected_edges)-1]

fields = ['Solution_Nb', 'Solution_value']
cursor = arcpy.da.InsertCursor(solution_info, fields)
cursor.insertRow((len(selected_edges)-1, solution_value))
del cursor

##### Store best solution
if (solution_value > best_solution_value):
    best_solution_value = solution_value
    best_solution_iteration = j
    best_solution_position = len(selected_edges)

# save solution's transversed edges per OD pair, total freight cost and TKU, new terminals by OD pair, volume
by new terminal
arcpy.conversion.TableToGeodatabase([outtable, nax_routes_path, tab_custo_frete_total, tab_junctions_route,
junctions_volume, used_new_rail_edges], best_solution_path)
nax_edges_path = out_path + "/" + "nax_edges"
arcpy.conversion.FeatureClassToGeodatabase(nax_edges_path, best_solution_path)

##### Calculating volume by edge and by transport mode - Just for best solution
# Calculating volume by edge
# add total volume field in nax_edges and update value
outtable = best_solution_path + "/" + "nax_edges_summary"
nax_routes_zero = best_solution_path + "/" + "nax_routes_zero"

arcpy.management.AddIndex(outtable, ["RouteID"], "Index4", "NON_UNIQUE", "ASCENDING")
arcpy.management.AddField(outtable, "vol_total", "DOUBLE")
arcpy.management.AddField(outtable, "RouteType", "TEXT")

```

```

with arcpy.da.UpdateCursor(outtable,["RouteID", "vol_total", "RouteType"]) as cur_5:
    for row_5 in cur_5:
        # calculate total volume
        with arcpy.da.SearchCursor(nax_routes_zero, ["ObjectID", "vol_total", "RouteType"]) as cur_6:
            for row_6 in cur_6:
                if(str(row_5[0])==str(row_6[0])):
                    row_5[1]=row_6[1]
                    row_5[2]=row_6[2]
                    break
            cur_5.updateRow(row_5)

# calculate transported volume in each edge - find volume by edge
tab_volume_trecho = arcpy.management.CreateTable(best_solution_path, "nax_edges_volume_summary")
statsFields2 = [{"vol_total", "SUM"}]
casefield2 = ["SourceName", "SourceOID", "FIRST_FromPosition", "LAST_ToPosition", "SUM_Attr_Length",
"SUM_Attr_Kilometers"]
arcpy.analysis.Statistics(outtable, tab_volume_trecho, statsFields2, casefield2)

# Run CalculateField - identify if is road or multimodal and calculate transported volume by mode
expression = "getTransportMode(!SourceName!)"
codeblock = ""
def getTransportMode(source):
    if source == "Ferro_Novo" or source == "PNL2017_Ferro_TermFerro" or source == "PNL2017_Ferrovias":
        return "Railway"
    elif source == "PNL2017_Hidro_Cabot" or source == "PNL2017_Hidro_Portos":
        return "Waterway"
    elif source == "PNL2017_Marit_OD" or source == "PNL2017_Marit_Portos" or source ==
"PNL2017_Marítimo":
        return "Maritime"
    else:
        return "Road" ""
arcpy.management.CalculateField(outtable, "TransportMode", expression, "PYTHON3", codeblock,
field_type="TEXT")

# calculate transported volume and TKU by transport mode
arcpy.management.CalculateField(outtable, "TKU", '!vol_total!*SUM_Attr_Length!', field_type="DOUBLE")

tab_volume_mod0 = arcpy.management.CreateTable(best_solution_path, "nax_edges_mod0_summary")
statsFields3 = [{"vol_total", "SUM"}, {"TKU", "SUM"}, {"SUM_Attr_Length", "SUM"}]
casefield3 = ["SourceName", "TransportMode", "RouteType"]
arcpy.analysis.Statistics(outtable, tab_volume_mod0, statsFields3, casefield3)

# export best solution data in an Excel file
nax_routes_path = best_solution_path + "/" + "nax_routes"
tab_custo_frete_total = best_solution_path + "/" + "nax_routes_summary"
tab_junctions_route = best_solution_path + "/" + "junctions_route"
junctions_volume = best_solution_path + "/" + "junctions_volume"
used_new_rail_edges = best_solution_path + "/" + "used_new_rail_edges"
tab_volume_trecho = best_solution_path + "/" + "nax_edges_volume_summary"
tab_volume_mod0 = best_solution_path + "/" + "nax_edges_mod0_summary"

arcpy.conversion.TableToExcel([nax_routes_path, outtable, tab_custo_frete_total, tab_junctions_route,
junctions_volume, used_new_rail_edges, tab_volume_trecho, tab_volume_mod0], "best_solution.xlsx")

# Calculate total processing time
later = datetime.datetime.now()
elapsed = later - now
print("Total processing time: ", elapsed)

```


APPENDIX B. Code for the supporting functions of the constructive heuristic of the railway network design model.

```

import arcpy
import datetime
import sys

def export_calculate_results(out_path, origins, result, flow_feature):
    # Export the results to a feature class
    arcpy.management.CreateFeatureclass(out_path, "nax_routes_zero", "", "", "", "", origins)
    nax_routes_zero = out_path + "/" + "nax_routes_zero"

    arcpy.management.CreateFeatureclass(out_path, "nax_edges_zero", "", "", "", "", origins)
    nax_edges_zero = out_path + "/" + "nax_edges_zero"

    if result.solveSucceeded:
        result.export(arcpy.nax.RouteOutputDataType.Routes, nax_routes_zero)
        result.export(arcpy.nax.RouteOutputDataType.RouteEdges, nax_edges_zero)
    else:
        print("Solver failed")
        print(result.solverMessages(arcpy.nax.MessageSeverity.All))

    # add total volume field in nax_routes and update value
    arcpy.management.AddIndex(nax_routes_zero, ["Name"], "Index2", "UNIQUE", "ASCENDING")
    try:
        arcpy.management.AddIndex(flow_feature, ["chave_reg_geo"], "FFIndex", "UNIQUE", "ASCENDING")
    except Exception:
        e = sys.exc_info()[1]
        print(e.args[0])
    arcpy.management.JoinField(nax_routes_zero, "Name", flow_feature, "chave_reg_geo", ["vol_total",
"RouteType"])

    # group edges in nax_edges - find transversed edges per OD pair
    outtable_zero = arcpy.management.CreateTable(out_path, "nax_edges_summary_zero")
    """ "Attr_Kilometers", etc. contains freight cost data, while "Attr_Length" contains distance (kilometers) data """
    statsFields = [{"FromPosition", "FIRST"}, {"ToPosition", "LAST"}, {"Attr_Length", "SUM"}, {"Attr_Kilometers",
"SUM"}, {"Cumul_Length", "MAX"}, {"Cumul_Kilometers", "MAX"}]
    casefield = ["SourceName", "SourceOID", "RouteID"]
    arcpy.analysis.Statistics(nax_edges_zero, outtable_zero, statsFields, casefield)

    return nax_routes_zero, nax_edges_zero, outtable_zero

def export_calculate_multimodal_results(out_path, origins, result, new_rail_terminals, new_rail_edges,
open_terminal_cost, building_unit_cost, expression2, codeblock2, nax_road_routes, total_freight_cost_zero,
expression4, codeblock4, expression5, codeblock5):
    ##### Export the results to a feature class
    arcpy.management.CreateFeatureclass(out_path, "nax_routes", "", "", "", "", origins)
    nax_routes_path = out_path + "/" + "nax_routes"

    arcpy.management.CreateFeatureclass(out_path, "nax_edges", "", "", "", "", origins)
    nax_edges_path = out_path + "/" + "nax_edges"

    arcpy.management.CreateFeatureclass(out_path, "nax_junctions", "", "", "", "", origins)
    nax_junctions_path = out_path + "/" + "nax_junctions"

    if result.solveSucceeded:
        result.export(arcpy.nax.RouteOutputDataType.Routes, nax_routes_path)
        result.export(arcpy.nax.RouteOutputDataType.RouteEdges, nax_edges_path)
        result.export(arcpy.nax.RouteOutputDataType.RouteJunctions, nax_junctions_path)
    else:
        print("Solver failed")
        print(result.solverMessages(arcpy.nax.MessageSeverity.All))

```

```

##### Calculate total freight cost
# add road mode freight cost and total volume field to the multimodal network data
arcpy.management.AddIndex(nax_routes_path, ["Name"], "Index2", "UNIQUE", "ASCENDING")
arcpy.management.JoinField(nax_routes_path, "Name", nax_road_routes, "Name", ["road_freight", "vol_total",
"RouteType"])

try:
    arcpy.management.AlterField(nax_routes_path, "Total_Kilometers", "multi_freight", "multi_freight")
except Exception:
    e = sys.exc_info()[1]
    print(e.args[0])

# apply allocation rule and calculate total transport cost per route
arcpy.management.CalculateField(nax_routes_path, "allocation_freight", expression4, "PYTHON3", codeblock4,
field_type="DOUBLE")
arcpy.management.CalculateField(nax_routes_path, "allocation_percentage_road", expression5, "PYTHON3",
codeblock5, field_type="DOUBLE")

# calculate total transport cost for the existing transportation network - per solution
tab_custo_frete_total = arcpy.management.CreateTable(out_path, "nax_routes_summary")
arcpy.analysis.Statistics(nax_routes_path, tab_custo_frete_total, [{"allocation_freight", "SUM"}, {"vol_total",
"SUM"}])

custo_frete_total = [row[0]for row in arcpy.da.SearchCursor(tab_custo_frete_total, ["SUM_allocation_freight"])]
diff_freight_cost = total_freight_cost_zero[0] - custo_frete_total[0]

##### Find the new railway junctions (terminals) used in the solution (COST)
# find the new railway junctions (terminals) used in the solution
arcpy.management.CreateFeatureclass(out_path, "used_new_rail_junctions", "", "", "", "", origins)
used_new_rail_junctions = out_path + "/" + "used_new_rail_junctions"

arcpy.management.AddIndex(nax_junctions_path, ["SourceName"], "Index6", "NON_UNIQUE",
"ASCENDING")
where_clause_2 = "SourceName" + " = " + new_rail_terminals + ""
temp_select2 = arcpy.management.SelectLayerByAttribute(nax_junctions_path, 'NEW_SELECTION',
where_clause_2)
arcpy.management.CopyFeatures(temp_select2, used_new_rail_junctions)

# summarize used junctions, find if there is one or more new railways
tab_junctions_route = arcpy.management.CreateTable(out_path, "junctions_route")
statsFields6 = [{"Cumul_Kilometers", "SUM"}]
casefield6 = ["RouteID"]
arcpy.analysis.Statistics(used_new_rail_junctions, tab_junctions_route, statsFields6, casefield6)

arcpy.management.CalculateField(tab_junctions_route, "Check", expression2, "PYTHON3", codeblock2,
field_type="TEXT")

# calculate total volume by terminal (access or exit)
arcpy.management.AddIndex(used_new_rail_junctions, ["RouteID"], "Index10", "NON_UNIQUE",
"ASCENDING")
arcpy.management.JoinField(used_new_rail_junctions, "RouteID", nax_routes_path, "ObjectID", ["vol_total",
"RouteType"])

junctions_volume = arcpy.management.CreateTable(out_path, "junctions_volume")
statsFields7 = [{"vol_total", "SUM"}]
casefield7 = ["SourceOID"]
arcpy.analysis.Statistics(used_new_rail_junctions, junctions_volume, statsFields7, casefield7)

# count number of terminals used in the solution
number_new_terminals = arcpy.management.GetCount(junctions_volume)
number_new_terminals_value = float(number_new_terminals[0])

```

```

##### Find the new railway edges used in the solution (COST)
# group edges in nax_edges - find transversed edges per OD pair
outtable = arcpy.management.CreateTable(out_path, "nax_edges_summary")
statsFields = [{"FromPosition", "FIRST"}, {"ToPosition", "LAST"}, {"Attr_Length", "SUM"}, {"Attr_Kilometers",
"SUM"}, {"Cumul_Length", "MAX"}, {"Cumul_Kilometers", "MAX"}]
casefield = ["SourceName", "SourceOID", "RouteID"]
arcpy.analysis.Statistics(nax_edges_path, outtable, statsFields, casefield)

# find the new railway edges used in the solution
used_new_rail_edges_per_route = arcpy.management.CreateTable(out_path, "used_new_rail_edges_per_route")
arcpy.management.AddIndex(outtable, ["SourceName"], "Index11", "NON_UNIQUE", "ASCENDING")
where_clause_3 = "SourceName" + " = " + new_rail_edges + ""
temp_select3 = arcpy.management.SelectLayerByAttribute(outtable, 'NEW_SELECTION', where_clause_3)
arcpy.management.CopyRows(temp_select3, used_new_rail_edges_per_route)

# add total volume field and update value
arcpy.management.AddIndex(used_new_rail_edges_per_route, ["RouteID"], "Index4", "NON_UNIQUE",
"ASCENDING")
arcpy.management.AddField(used_new_rail_edges_per_route, "vol_total", "DOUBLE")
arcpy.management.AddField(used_new_rail_edges_per_route, "RouteType", "TEXT")
with arcpy.da.UpdateCursor(used_new_rail_edges_per_route, ["RouteID", "vol_total", "RouteType"]) as cur_5:
    for row_5 in cur_5:
        # calculate total volume
        with arcpy.da.SearchCursor(nax_routes_path, ["ObjectID", "vol_total", "RouteType"]) as cur_6:
            for row_6 in cur_6:
                if(str(row_5[0])==str(row_6[0])):
                    row_5[1]=row_6[1]
                    row_5[2]=row_6[2]
                    break
            cur_5.updateRow(row_5)

# summarize edges used in the solution
used_new_rail_edges = arcpy.management.CreateTable(out_path, "used_new_rail_edges")
statsFields2 = [{"vol_total", "SUM"}]
casefield2 = ["SourceName", "SourceOID", "SUM_Attr_Length", "SUM_Attr_Kilometers", "RouteType"]
arcpy.analysis.Statistics(used_new_rail_edges_per_route, used_new_rail_edges, statsFields2, casefield2)

##### Calculate solution value (COST BENEFIT RATIO)
used_new_rail_edges_group = arcpy.management.CreateTable(out_path, "used_new_rail_edges_group")
statsFields3 = [{"vol_total", "SUM"}]
casefield3 = ["SourceName", "SourceOID", "SUM_Attr_Length", "SUM_Attr_Kilometers"]
arcpy.analysis.Statistics(used_new_rail_edges_per_route, used_new_rail_edges_group, statsFields3, casefield3)

# calculate new railway's edges construction cost
arcpy.management.CalculateField(used_new_rail_edges_group, "building_cost",
"building_unit_cost!*SUM_Attr_Length!", field_type="DOUBLE")

# calculate new railway's construction cost (edges and junctions (terminals)
total_building_cost = arcpy.management.CreateTable(out_path, "total_building_cost")
arcpy.analysis.Statistics(used_new_rail_edges_group, total_building_cost, [{"building_cost", "SUM"}])
total_building_cost_value = [row[0]for row in arcpy.da.SearchCursor(total_building_cost,
["SUM_building_cost"])]

if(number_new_terminals_value>0):
    total_building_cost_value2 = float(total_building_cost_value[0])
    # store value - solution
    solution_value = diff_freight_cost / ((number_new_terminals_value * open_terminal_cost) +
total_building_cost_value2)
else:
    solution_value = 0

```

```

    return solution_value, junctions_volume, tab_custo_frete_total, tab_junctions_route, used_new_rail_edges,
    outtable, nax_routes_path, nax_edges_path

```

```

def prepare_network_dataset(new_rail_edges_path, new_network_location, new_rail_edges, selected_edges,
solution, count, used_new_rail_edges_initial_group_sort, minimum_edge_volume):

```

```

    # find the edges that are going to be selected
    arcpy.conversion.FeatureClassToGeodatabase(new_rail_edges_path, new_network_location)
    selected_rail_edges = new_network_location + "/" + new_rail_edges
    arcpy.management.AddIndex(selected_rail_edges, ["ID"], "Index2", "UNIQUE", "ASCENDING")
    arcpy.management.CalculateField(selected_rail_edges, "Keep", 0, field_type="SHORT")

```

```

    lower_bound = count * minimum_edge_volume
    where_clause_3 = "MAX_SUM_vol_total" + " >= " + str(lower_bound)
    temp_select3 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges_initial_group_sort,
'NEW_SELECTION', where_clause_3)

```

```

    with arcpy.da.UpdateCursor(selected_rail_edges, ["ID", "Keep", "StartPtID", "EndPtID", "SUM_vol_total"]) as
cur_13:

```

```

        for row_13 in cur_13:

```

```

            with arcpy.da.SearchCursor(temp_select3, ["ObjectID_Num", "StartPtID", "EndPtID"]) as cur_12:

```

```

                for row_12 in cur_12:

```

```

                    if(row_13[2] == row_12[1] and row_13[3] == row_12[2]):

```

```

                        row_13[1] = 1

```

```

                        cur_13.updateRow(row_13)

```

```

                        break

```

```

    # delete non selected edges

```

```

    where_clause_4 = "Keep" = 0'

```

```

    temp_select4 = arcpy.management.SelectLayerByAttribute(selected_rail_edges, 'NEW_SELECTION',
where_clause_4)

```

```

    arcpy.management.DeleteRows(temp_select4)

```

```

    # save selected edges (solution)

```

```

    selected_edges[solution] = []

```

```

    with arcpy.da.SearchCursor(selected_rail_edges, ["ID"]) as cur_11:

```

```

        for row_11 in cur_11:

```

```

            selected_edges[solution].append(row_11[0])

```

```

    return lower_bound, selected_rail_edges

```

```

def local_search(out_path, new_rail_edges_path, selected_rail_edges, new_rail_edges, new_network_location, count,
selected_edges, used_new_rail_edges, test9, test8, test7, test6, test5, test4, test3, test2, test1, minimum_edge_volume,
lower_bound):

```

```

    # create Feature Class with current solution selected edges

```

```

    if(count==0):

```

```

        arcpy.conversion.FeatureClassToGeodatabase(selected_rail_edges, out_path)

```

```

        try:

```

```

            arcpy.management.Delete(selected_rail_edges)

```

```

        except Exception:

```

```

            e = sys.exc_info()[1]

```

```

            print(e.args[0])

```

```

        selected_rail_edges = out_path + "/" + new_rail_edges

```

```

    # find used new rail edges

```

```

    Type = "Domestic"

```

```

    used_new_rail_edges_domestic = arcpy.management.CreateTable(out_path, "used_new_rail_edges_domestic")

```

```

    where_clause_2 = "RouteType" + " = " + Type + ""

```

```

temp_select2 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges, 'NEW_SELECTION',
where_clause_2)
arcpy.management.CopyRows(temp_select2, used_new_rail_edges_domestic)

# alter SUM_vol_total name, so is different from the field in selected_rail_edges (initial solution volume)
try:
    arcpy.management.AlterField(used_new_rail_edges_domestic, "SUM_vol_total", "best_solution_volume",
"best_solution_volume")
except Exception:
    e = sys.exc_info()[1]
    print(e.args[0])

# add best solution volume to selected_rail_edges
arcpy.management.AddIndex(used_new_rail_edges_domestic, ["SourceOID"], "Index2", "UNIQUE",
"ASCENDING")
arcpy.management.JoinField(selected_rail_edges, "ID", used_new_rail_edges_domestic, "SourceOID",
["best_solution_volume"])

# remove null values
where_clause_4 = "'best_solution_volume' is null"
temp_select4 = arcpy.management.SelectLayerByAttribute(selected_rail_edges, 'NEW_SELECTION',
where_clause_4)
arcpy.management.CalculateField(temp_select4, "best_solution_volume", 0)
arcpy.management.SelectLayerByAttribute(selected_rail_edges, 'CLEAR_SELECTION')

# create Feature Class with adjacent edges
arcpy.conversion.FeatureClassToGeodatabase(new_rail_edges_path, new_network_location)
adjacent_edges = new_network_location + "/" + new_rail_edges
arcpy.management.AddIndex(adjacent_edges, ["ID"], "Index2", "UNIQUE", "ASCENDING")
arcpy.management.CalculateField(adjacent_edges, "Keep_used", 0, field_type="SHORT")
arcpy.management.CalculateField(adjacent_edges, "Keep_selected", 0, field_type="SHORT")

# prepare the iteration
test9 = 0
test8 = 0
test7 = 0
test6 = 0
test5 = 0
test4 = 0
test3 = 0
test2 = 0
test1 = 0

# find and insert adjacent edges
with arcpy.da.UpdateCursor(adjacent_edges, ["ID", "StartPtID", "EndPtID", "Keep_used", "SUM_vol_total",
"Keep_selected"]) as cur_c:
    for row_c in cur_c:
        with arcpy.da.SearchCursor(selected_rail_edges, ["ID", "StartPtID", "EndPtID",
"best_solution_volume"]) as cur_d:
            for row_d in cur_d:
                # selected new rail edges
                if(row_c[0]==row_d[0]):
                    # remove selected, not used
                    if(row_d[3]==0):
                        row_c[3] = 5
                        row_c[5] = 5
                        cur_c.updateRow(row_c)
                        # if there is no chance in improving "keep" value, break
                        break
                # remove used, but with volume lower than minimum
                elif(row_d[3]<minimum_edge_volume):
                    row_c[3] = 10

```

```

        row_c[5] = 10
        cur_c.updateRow(row_c)
        # if there is no chance in improving "keep" value, break
        break
    # keep used with volume higher than minimum
    elif(row_d[3]>=minimum_edge_volume):
        row_c[3] = 11
        row_c[5] = 11
        cur_c.updateRow(row_c)
        # if there is no chance in improving "keep" value, break
        break
    # add adjacent edges with high initial volume to used new rail edges
    if((row_c[0]!=row_d[0] and ((row_c[1]!=row_d[1] or row_c[1]==row_d[2]) or (row_c[2]==row_d[1]
or row_c[2]==row_d[2])) and row_d[3]>0):
        # adjacent edge with chance to improve "keep" value and with initial volume greater than 90% of
lower_bound
        if((row_c[3]<9) and (row_c[4]>=0.9*lower_bound)):
            row_c[3] = 9
            cur_c.updateRow(row_c)
            # adjacent edge with chance to improve "keep" value and with initial volume greater than 80% of
lower_bound
            elif((row_c[3]<8) and (row_c[4]<0.9*lower_bound and row_c[4]>=0.8*lower_bound)):
                row_c[3] = 8
                cur_c.updateRow(row_c)
                # adjacent edge with chance to improve "keep" value and with initial volume greater than 70% of
lower_bound
                elif((row_c[3]<7) and (row_c[4]<0.8*lower_bound and row_c[4]>=0.7*lower_bound)):
                    row_c[3] = 7
                    cur_c.updateRow(row_c)
                    # adjacent edge with chance to improve "keep" value and with initial volume greater than
minimum_edge_volume
                    elif((row_c[3]<6) and (row_c[4]<0.7*lower_bound and row_c[4]>=minimum_edge_volume)):
                        row_c[3] = 6
                        cur_c.updateRow(row_c)
                        # add adjacent edges with high initial volume to selected new rail edges
                        if((row_c[0]!=row_d[0] and ((row_c[1]==row_d[1] or row_c[1]==row_d[2]) or (row_c[2]==row_d[1]
or row_c[2]==row_d[2])) and row_d[3]>=0):
                            # adjacent edge with chance to improve "keep" value and with initial volume greater than 90% of
lower_bound
                            if((row_c[5]<4) and (row_c[4]>=0.9*lower_bound)):
                                row_c[5] = 4
                                cur_c.updateRow(row_c)
                                # adjacent edge with chance to improve "keep" value and with initial volume greater than 80% of
lower_bound
                                elif((row_c[5]<3) and (row_c[4]<0.9*lower_bound and row_c[4]>=0.8*lower_bound)):
                                    row_c[5] = 3
                                    cur_c.updateRow(row_c)
                                    # adjacent edge with chance to improve "keep" value and with initial volume greater than 70% of
lower_bound
                                    elif((row_c[5]<2) and (row_c[4]<0.8*lower_bound and row_c[4]>=0.7*lower_bound)):
                                        row_c[5] = 2
                                        cur_c.updateRow(row_c)
                                        # adjacent edge with chance to improve "keep" value and with initial volume greater than
minimum_edge_volume
                                        elif((row_c[5]<1) and (row_c[4]<0.7*lower_bound and row_c[4]>=minimum_edge_volume)):
                                            row_c[5] = 1
                                            cur_c.updateRow(row_c)

# update test variables
where_clause_1 = "Keep_used" <> 0'
temp_select1 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_1)

```

```

with arcpy.da.SearchCursor(temp_select1, ["Keep_used"]) as cur_a:
    for row_a in cur_a:
        if(row_a[0]==9):
            test9 += 1
        elif(row_a[0]==8):
            test8 += 1
        elif(row_a[0]==7):
            test7 += 1
        elif(row_a[0]==6):
            test6 += 1
        elif(row_a[0]==5):
            test5 += 1

    where_clause_1 = "Keep_selected" <> 0'
    temp_select1 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_1)

with arcpy.da.SearchCursor(temp_select1, ["Keep_selected"]) as cur_a:
    for row_a in cur_a:
        if(row_a[0]==4):
            test4 += 1
        elif(row_a[0]==3):
            test3 += 1
        elif(row_a[0]==2):
            test2 += 1
        elif(row_a[0]==1):
            test1 += 1

# copy adjacent edges to out_path - store for next iterations
arcpy.conversion.FeatureClassToGeodatabase(adjacent_edges, out_path)
arcpy.conversion.TableToExcel(adjacent_edges, "adjacent_edges" + str(len(selected_edges)) + ".xlsx")

elif(count>0):
    try:
        arcpy.management.Delete(selected_rail_edges)
    except Exception:
        e = sys.exc_info()[1]
        print(e.args[0])

# create Feature Class with adjacent edges - with "keep" information from count = 0
adjacent_edges = out_path + "/" + new_rail_edges
arcpy.conversion.FeatureClassToGeodatabase(adjacent_edges, new_network_location)
adjacent_edges = new_network_location + "/" + new_rail_edges

if(count==0):
    # keep used edges and adjacent edges with high initial value
    if(test9 > 0):
        where_clause_5 = "Keep_used" < 9'
    elif(test8 > 0):
        where_clause_5 = "Keep_used" < 8'
    elif(test7 > 0):
        where_clause_5 = "Keep_used" < 7'
    else:
        where_clause_5 = "Keep_used" < 6'
    temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
    arcpy.management.DeleteRows(temp_select5)
elif(count==1):
    # keep used edges and adjacent edges with high initial value
    if(test9 > 0 and test8 > 0):
        where_clause_5 = "Keep_used" < 8'

```

```

elif((test9 > 0 or test8 > 0) and test7 > 0):
    where_clause_5 = "Keep_used" < 7'
else:
    where_clause_5 = "Keep_used" < 6'
temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
arcpy.management.DeleteRows(temp_select5)
elif(count==2):
    # keep selected edges and adjacent edges with high initial value
    if(test4 > 0):
        where_clause_5 = "Keep_selected" < 4'
    elif(test3 > 0):
        where_clause_5 = "Keep_selected" < 3'
    elif(test2 > 0):
        where_clause_5 = "Keep_selected" < 2'
    else:
        where_clause_5 = "Keep_selected" < 1'
temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
arcpy.management.DeleteRows(temp_select5)
elif(count==3):
    # keep selected edges and adjacent edges with high initial value
    if(test4 > 0 and test3 > 0):
        where_clause_5 = "Keep_selected" < 3'
    elif((test4 > 0 or test3 > 0) and test2 > 0):
        where_clause_5 = "Keep_selected" < 2'
    else:
        where_clause_5 = "Keep_selected" < 1'
temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
arcpy.management.DeleteRows(temp_select5)

# save selected edges (solution)
solution = len(selected_edges)
selected_edges[solution] = []

with arcpy.da.SearchCursor(adjacent_edges, ["ID"]) as cur_11:
    for row_11 in cur_11:
        selected_edges[solution].append(row_11[0])

# prepare file for network dataset
selected_rail_edges = new_network_location + "/" + new_rail_edges

return test9, test8, test7, test6, test5, test4, test3, test2, test1

def local_search_best(best_selected_rail_edges, best_solution_path, out_path, new_rail_edges_path,
selected_rail_edges, new_rail_edges, new_network_location, count, selected_edges, used_new_rail_edges, btest9,
btest8, btest7, btest6, btest5, btest4, btest3, btest2, btest1, minimum_edge_volume, lower_bound):

# create Feature Class with current solution selected edges
if(count==0):
    try:
        arcpy.management.Delete(best_selected_rail_edges)
    except Exception:
        e = sys.exc_info()[1]
        print(e.args[0])
    arcpy.conversion.FeatureClassToGeodatabase(selected_rail_edges, best_solution_path)
    best_selected_rail_edges = best_solution_path + "/" + new_rail_edges
    try:
        arcpy.management.Delete(selected_rail_edges)
    except Exception:
        e = sys.exc_info()[1]

```



```

print(e.args[0])

# find used new rail edges
Type = "Domestic"
used_new_rail_edges_domestic = arcpy.management.CreateTable(out_path, "used_new_rail_edges_domestic")
where_clause_2 = "'RouteType'" + " = '" + Type + "'"
temp_select2 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges, 'NEW_SELECTION',
where_clause_2)
arcpy.management.CopyRows(temp_select2, used_new_rail_edges_domestic)

# alter SUM_vol_total name, so is different from the field in selected_rail_edges (initial solution volume)
try:
    arcpy.management.AlterField(used_new_rail_edges_domestic, "SUM_vol_total", "best_solution_volume",
"best_solution_volume")
except Exception:
    e = sys.exc_info()[1]
    print(e.args[0])

# add best solution volume to selected_rail_edges
arcpy.management.AddIndex(used_new_rail_edges_domestic, ["SourceOID"], "Index2", "UNIQUE",
"ASCENDING")
arcpy.management.JoinField(best_selected_rail_edges, "ID", used_new_rail_edges_domestic, "SourceOID",
["best_solution_volume"])

# remove null values
where_clause_4 = "'best_solution_volume' is null"
temp_select4 = arcpy.management.SelectLayerByAttribute(best_selected_rail_edges, 'NEW_SELECTION',
where_clause_4)
arcpy.management.CalculateField(temp_select4, "best_solution_volume", 0)
arcpy.management.SelectLayerByAttribute(best_selected_rail_edges, 'CLEAR_SELECTION')

# create Feature Class with adjacent edges
arcpy.conversion.FeatureClassToGeodatabase(new_rail_edges_path, new_network_location)
adjacent_edges = new_network_location + "/" + new_rail_edges
arcpy.management.AddIndex(adjacent_edges, ["ID"], "Index2", "UNIQUE", "ASCENDING")
arcpy.management.CalculateField(adjacent_edges, "Keep_used", 0, field_type="SHORT")
arcpy.management.CalculateField(adjacent_edges, "Keep_selected", 0, field_type="SHORT")

# delete rows with low volume - DON'T!!!! will lose SourceOID info

# prepare the iteration
btest9 = 0
btest8 = 0
btest7 = 0
btest6 = 0
btest5 = 0
btest4 = 0
btest3 = 0
btest2 = 0
btest1 = 0

# find and insert adjacent edges
with arcpy.da.UpdateCursor(adjacent_edges, ["ID", "StartPtID", "EndPtID", "Keep_used", "SUM_vol_total",
"Keep_selected"]) as cur_c:
    for row_c in cur_c:
        with arcpy.da.SearchCursor(best_selected_rail_edges, ["ID", "StartPtID", "EndPtID",
"best_solution_volume"]) as cur_d:
            for row_d in cur_d:
                # selected new rail edges
                if(row_c[0]==row_d[0]):
                    # remove selected, not used
                    if(row_d[3]==0):

```

```

    row_c[3] = 5
    row_c[5] = 5
    cur_c.updateRow(row_c)
    # if there is no chance in improving "keep" value, break
    break
# remove used, but with volume lower than minimum
elif(row_d[3]<minimum_edge_volume):
    row_c[3] = 10
    row_c[5] = 10
    cur_c.updateRow(row_c)
    # if there is no chance in improving "keep" value, break
    break
# keep used with volume higher than minimum
elif(row_d[3]>=minimum_edge_volume):
    row_c[3] = 11
    row_c[5] = 11
    cur_c.updateRow(row_c)
    # if there is no chance in improving "keep" value, break
    break
# add adjacent edges with high initial volume to used new rail edges
if((row_c[0]!=row_d[0] and ((row_c[1]==row_d[1] or row_c[1]==row_d[2]) or (row_c[2]==row_d[1]
or row_c[2]==row_d[2])) and row_d[3]>0):
    # adjacent edge with chance to improve "keep" value and with initial volume greater than 90% of
lower_bound
    if((row_c[3]<9) and (row_c[4]>=0.9*lower_bound)):
        row_c[3] = 9
        cur_c.updateRow(row_c)
    # adjacent edge with chance to improve "keep" value and with initial volume greater than 80% of
lower_bound
    elif((row_c[3]<8) and (row_c[4]<0.9*lower_bound and row_c[4]>=0.8*lower_bound)):
        row_c[3] = 8
        cur_c.updateRow(row_c)
    # adjacent edge with chance to improve "keep" value and with initial volume greater than 70% of
lower_bound
    elif((row_c[3]<7) and (row_c[4]<0.8*lower_bound and row_c[4]>=0.7*lower_bound)):
        row_c[3] = 7
        cur_c.updateRow(row_c)
    # adjacent edge with chance to improve "keep" value and with initial volume greater than
minimum_edge_volume
    elif((row_c[3]<6) and (row_c[4]<0.7*lower_bound and row_c[4]>=minimum_edge_volume)):
        row_c[3] = 6
        cur_c.updateRow(row_c)
# add adjacent edges with high initial volume to selected new rail edges
if((row_c[0]!=row_d[0] and ((row_c[1]==row_d[1] or row_c[1]==row_d[2]) or (row_c[2]==row_d[1]
or row_c[2]==row_d[2])) and row_d[3]>=0):
    # adjacent edge with chance to improve "keep" value and with initial volume greater than 90% of
lower_bound
    if((row_c[5]<4) and (row_c[4]>=0.9*lower_bound)):
        row_c[5] = 4
        cur_c.updateRow(row_c)
    # adjacent edge with chance to improve "keep" value and with initial volume greater than 80% of
lower_bound
    elif((row_c[5]<3) and (row_c[4]<0.9*lower_bound and row_c[4]>=0.8*lower_bound)):
        row_c[5] = 3
        cur_c.updateRow(row_c)
    # adjacent edge with chance to improve "keep" value and with initial volume greater than 70% of
lower_bound
    elif((row_c[5]<2) and (row_c[4]<0.8*lower_bound and row_c[4]>=0.7*lower_bound)):
        row_c[5] = 2
        cur_c.updateRow(row_c)
    # adjacent edge with chance to improve "keep" value and with initial volume greater than
minimum_edge_volume

```

```

        elif((row_c[5]<1) and (row_c[4]<0.7*lower_bound and row_c[4]>=minimum_edge_volume)):
            row_c[5] = 1
            cur_c.updateRow(row_c)

# update test variables
where_clause_1 = "Keep_used" <> 0'
temp_select1 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_1)

with arcpy.da.SearchCursor(temp_select1, ["Keep_used"]) as cur_a:
    for row_a in cur_a:
        if(row_a[0]==9):
            btest9 += 1
        elif(row_a[0]==8):
            btest8 += 1
        elif(row_a[0]==7):
            btest7 += 1
        elif(row_a[0]==6):
            btest6 += 1
        elif(row_a[0]==5):
            btest5 += 1

where_clause_1 = "Keep_selected" <> 0'
temp_select1 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_1)

with arcpy.da.SearchCursor(temp_select1, ["Keep_selected"]) as cur_a:
    for row_a in cur_a:
        if(row_a[0]==4):
            btest4 += 1
        elif(row_a[0]==3):
            btest3 += 1
        elif(row_a[0]==2):
            btest2 += 1
        elif(row_a[0]==1):
            btest1 += 1

# copy adjacent edges to best_solution_path - store for next iterations
try:
    arcpy.management.Delete(best_selected_rail_edges)
except Exception:
    e = sys.exc_info()[1]
    print(e.args[0])
arcpy.conversion.FeatureClassToGeodatabase(adjacent_edges, best_solution_path)
arcpy.conversion.TableToExcel(adjacent_edges, "adjacent_edges" + str(len(selected_edges)) + ".xlsx")

elif(count>0):
    try:
        arcpy.management.Delete(selected_rail_edges)
    except Exception:
        e = sys.exc_info()[1]
        print(e.args[0])

# create Feature Class with adjacent edges - with "keep" information from count = 0
adjacent_edges = best_solution_path + "/" + new_rail_edges
arcpy.conversion.FeatureClassToGeodatabase(adjacent_edges, new_network_location)
adjacent_edges = new_network_location + "/" + new_rail_edges

if(count==0):
    # keep used edges and adjacent edges with high initial value
    if(btest9 > 0):
        where_clause_5 = "Keep_used" < 9'

```

```

elif(bttest8 > 0):
    where_clause_5 = "'Keep_used' < 8'"
elif(bttest7 > 0):
    where_clause_5 = "'Keep_used' < 7'"
else:
    where_clause_5 = "'Keep_used' < 6'"
temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
arcpy.management.DeleteRows(temp_select5)
elif(count==1):
    # keep used edges and adjacent edges with high initial value
    if(bttest9 > 0 and bttest8 > 0):
        where_clause_5 = "'Keep_used' < 8'"
    elif((bttest9 > 0 or bttest8 > 0) and bttest7 > 0):
        where_clause_5 = "'Keep_used' < 7'"
    else:
        where_clause_5 = "'Keep_used' < 6'"
temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
arcpy.management.DeleteRows(temp_select5)
elif(count==2):
    # keep selected edges and adjacent edges with high initial value
    if(bttest4 > 0):
        where_clause_5 = "'Keep_selected' < 4'"
    elif(bttest3 > 0):
        where_clause_5 = "'Keep_selected' < 3'"
    elif(bttest2 > 0):
        where_clause_5 = "'Keep_selected' < 2'"
    else:
        where_clause_5 = "'Keep_selected' < 1'"
temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
arcpy.management.DeleteRows(temp_select5)
elif(count==3):
    # keep selected edges and adjacent edges with high initial value
    if(bttest4 > 0 and bttest3 > 0):
        where_clause_5 = "'Keep_selected' < 3'"
    elif((bttest4 > 0 or bttest3 > 0) and bttest2 > 0):
        where_clause_5 = "'Keep_selected' < 2'"
    else:
        where_clause_5 = "'Keep_selected' < 1'"
temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
arcpy.management.DeleteRows(temp_select5)

# save selected edges (solution)
solution = len(selected_edges)
selected_edges[solution] = []

with arcpy.da.SearchCursor(adjacent_edges, ["ID"]) as cur_11:
    for row_11 in cur_11:
        selected_edges[solution].append(row_11[0])

# prepare file for network dataset
selected_rail_edges = new_network_location + "/" + new_rail_edges

return bttest9, bttest8, bttest7, bttest6, bttest5, bttest4, bttest3, bttest2, bttest1

def local_search_best_final(best_selected_rail_edges, best_solution_path, out_path, new_rail_edges_path,
selected_rail_edges, new_rail_edges, new_network_location, count, selected_edges, used_new_rail_edges, bttest9,
bttest8, bttest7, bttest6, bttest5, bttest4, bttest3, bttest2, bttest1, minimum_edge_volume, lower_bound):

```

```

# create Feature Class with current solution selected edges
if(count==0):
    try:
        arcpy.management.Delete(selected_rail_edges)
    except Exception:
        e = sys.exc_info()[1]
        print(e.args[0])

# find used new rail edges
Type = "Domestic"
used_new_rail_edges_domestic = arcpy.management.CreateTable(out_path, "used_new_rail_edges_domestic")
where_clause_2 = "RouteType" + " = " + Type + ""
temp_select2 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges, 'NEW_SELECTION',
where_clause_2)
arcpy.management.CopyRows(temp_select2, used_new_rail_edges_domestic)

# alter SUM_vol_total name, so is different from the field in selected_rail_edges (initial solution volume)
try:
    arcpy.management.AlterField(used_new_rail_edges_domestic, "SUM_vol_total",
"best_solution_volume_final", "best_solution_volume_final")
except Exception:
    e = sys.exc_info()[1]
    print(e.args[0])

# add best solution volume to selected_rail_edges
arcpy.management.AddIndex(used_new_rail_edges_domestic, ["SourceOID"], "Index2", "UNIQUE",
"ASCENDING")
arcpy.management.JoinField(best_selected_rail_edges, "ID", used_new_rail_edges_domestic, "SourceOID",
["best_solution_volume_final"])

# remove null values
where_clause_4 = "best_solution_volume_final" is null'
temp_select4 = arcpy.management.SelectLayerByAttribute(best_selected_rail_edges, 'NEW_SELECTION',
where_clause_4)
arcpy.management.CalculateField(temp_select4, "best_solution_volume_final", 0)
arcpy.management.SelectLayerByAttribute(best_selected_rail_edges, 'CLEAR_SELECTION')

# create Feature Class with adjacent edges
arcpy.conversion.FeatureClassToGeodatabase(new_rail_edges_path, new_network_location)
adjacent_edges = new_network_location + "/" + new_rail_edges
arcpy.management.AddIndex(adjacent_edges, ["ID"], "Index2", "UNIQUE", "ASCENDING")
arcpy.management.CalculateField(adjacent_edges, "Keep_used", 0, field_type="SHORT")
arcpy.management.CalculateField(adjacent_edges, "Keep_selected", 0, field_type="SHORT")

# prepare the iteration
btest9 = 0
btest8 = 0
btest7 = 0
btest6 = 0
btest5 = 0
btest4 = 0
btest3 = 0
btest2 = 0
btest1 = 0

# find and insert adjacent edges
with arcpy.da.UpdateCursor(adjacent_edges, ["ID", "StartPtID", "EndPtID", "Keep_used", "SUM_vol_total",
"Keep_selected"]) as cur_c:
    for row_c in cur_c:
        with arcpy.da.SearchCursor(best_selected_rail_edges, ["ID", "StartPtID", "EndPtID",
"best_solution_volume_final"]) as cur_d:

```

```

for row_d in cur_d:
    # selected new rail edges
    if(row_c[0]==row_d[0]):
        # remove selected, not used
        if(row_d[3]==0):
            row_c[3] = 5
            row_c[5] = 5
            cur_c.updateRow(row_c)
            # if there is no chance in improving "keep" value, break
            break
        # remove used, but with volume lower than minimum
        elif(row_d[3]<minimum_edge_volume):
            row_c[3] = 10
            row_c[5] = 10
            cur_c.updateRow(row_c)
            # if there is no chance in improving "keep" value, break
            break
        # keep used with volume higher than minimum
        elif(row_d[3]>=minimum_edge_volume):
            row_c[3] = 11
            row_c[5] = 11
            cur_c.updateRow(row_c)
            # if there is no chance in improving "keep" value, break
            break
    # add adjacent edges with high initial volume to used new rail edges
    if(row_c[0]!=row_d[0] and ((row_c[1]==row_d[1] or row_c[1]==row_d[2]) or (row_c[2]==row_d[1]
or row_c[2]==row_d[2])) and row_d[3]>0):
        # adjacent edge with chance to improve "keep" value and with initial volume greater than 90% of
lower_bound
        if((row_c[3]<9) and (row_c[4]>=0.9*lower_bound)):
            row_c[3] = 9
            cur_c.updateRow(row_c)
        # adjacent edge with chance to improve "keep" value and with initial volume greater than 80% of
lower_bound
        elif((row_c[3]<8) and (row_c[4]<0.9*lower_bound and row_c[4]>=0.8*lower_bound)):
            row_c[3] = 8
            cur_c.updateRow(row_c)
        # adjacent edge with chance to improve "keep" value and with initial volume greater than 70% of
lower_bound
        elif((row_c[3]<7) and (row_c[4]<0.8*lower_bound and row_c[4]>=0.7*lower_bound)):
            row_c[3] = 7
            cur_c.updateRow(row_c)
        # adjacent edge with chance to improve "keep" value and with initial volume greater than
minimum_edge_volume
        elif((row_c[3]<6) and (row_c[4]<0.7*lower_bound and row_c[4]>=minimum_edge_volume)):
            row_c[3] = 6
            cur_c.updateRow(row_c)
    # add adjacent edges with high initial volume to selected new rail edges
    if(row_c[0]!=row_d[0] and ((row_c[1]==row_d[1] or row_c[1]==row_d[2]) or (row_c[2]==row_d[1]
or row_c[2]==row_d[2])) and row_d[3]>=0):
        # adjacent edge with chance to improve "keep" value and with initial volume greater than 90% of
lower_bound
        if((row_c[5]<4) and (row_c[4]>=0.9*lower_bound)):
            row_c[5] = 4
            cur_c.updateRow(row_c)
        # adjacent edge with chance to improve "keep" value and with initial volume greater than 80% of
lower_bound
        elif((row_c[5]<3) and (row_c[4]<0.9*lower_bound and row_c[4]>=0.8*lower_bound)):
            row_c[5] = 3
            cur_c.updateRow(row_c)
        # adjacent edge with chance to improve "keep" value and with initial volume greater than 70% of
lower_bound

```

```

        elif((row_c[5]<2) and (row_c[4]<0.8*lower_bound and row_c[4]>=0.7*lower_bound)):
            row_c[5] = 2
            cur_c.updateRow(row_c)
            # adjacent edge with chance to improve "keep" value and with initial volume greater than
minimum_edge_volume
        elif((row_c[5]<1) and (row_c[4]<0.7*lower_bound and row_c[4]>=minimum_edge_volume)):
            row_c[5] = 1
            cur_c.updateRow(row_c)

# update test variables
where_clause_1 = "'Keep_used' <> 0'
temp_select1 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_1)

with arcpy.da.SearchCursor(temp_select1, ["Keep_used"]) as cur_a:
    for row_a in cur_a:
        if(row_a[0]==9):
            btest9 += 1
        elif(row_a[0]==8):
            btest8 += 1
        elif(row_a[0]==7):
            btest7 += 1
        elif(row_a[0]==6):
            btest6 += 1
        elif(row_a[0]==5):
            btest5 += 1

where_clause_1 = "'Keep_selected' <> 0'
temp_select1 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_1)

with arcpy.da.SearchCursor(temp_select1, ["Keep_selected"]) as cur_a:
    for row_a in cur_a:
        if(row_a[0]==4):
            btest4 += 1
        elif(row_a[0]==3):
            btest3 += 1
        elif(row_a[0]==2):
            btest2 += 1
        elif(row_a[0]==1):
            btest1 += 1

# copy adjacent edges to best_solution_path - store for next iterations
try:
    arcpy.management.Delete(best_selected_rail_edges)
except Exception:
    e = sys.exc_info()[1]
    print(e.args[0])
arcpy.conversion.FeatureClassToGeodatabase(adjacent_edges, best_solution_path)
arcpy.conversion.TableToExcel(adjacent_edges, "adjacent_edges" + str(len(selected_edges)) + ".xlsx")

elif(count>0):
    try:
        arcpy.management.Delete(selected_rail_edges)
    except Exception:
        e = sys.exc_info()[1]
        print(e.args[0])

# create Feature Class with adjacent edges - with "keep" information from count = 0
adjacent_edges = best_solution_path + "/" + new_rail_edges
arcpy.conversion.FeatureClassToGeodatabase(adjacent_edges, new_network_location)
adjacent_edges = new_network_location + "/" + new_rail_edges

```

```

if(count==0):
    # keep used edges and adjacent edges with high initial value
    if(bttest9 > 0):
        where_clause_5 = "'Keep_used' < 9'
    elif(bttest8 > 0):
        where_clause_5 = "'Keep_used' < 8'
    elif(bttest7 > 0):
        where_clause_5 = "'Keep_used' < 7'
    else:
        where_clause_5 = "'Keep_used' < 6'
    temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
    arcpy.management.DeleteRows(temp_select5)
elif(count==1):
    # keep used edges and adjacent edges with high initial value
    if(bttest9 > 0 and bttest8 > 0):
        where_clause_5 = "'Keep_used' < 8'
    elif((bttest9 > 0 or bttest8 > 0) and bttest7 > 0):
        where_clause_5 = "'Keep_used' < 7'
    else:
        where_clause_5 = "'Keep_used' < 6'
    temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
    arcpy.management.DeleteRows(temp_select5)
elif(count==2):
    # keep selected edges and adjacent edges with high initial value
    if(bttest4 > 0):
        where_clause_5 = "'Keep_selected' < 4'
    elif(bttest3 > 0):
        where_clause_5 = "'Keep_selected' < 3'
    elif(bttest2 > 0):
        where_clause_5 = "'Keep_selected' < 2'
    else:
        where_clause_5 = "'Keep_selected' < 1'
    temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
    arcpy.management.DeleteRows(temp_select5)
elif(count==3):
    # keep selected edges and adjacent edges with high initial value
    if(bttest4 > 0 and bttest3 > 0):
        where_clause_5 = "'Keep_selected' < 3'
    elif((bttest4 > 0 or bttest3 > 0) and bttest2 > 0):
        where_clause_5 = "'Keep_selected' < 2'
    else:
        where_clause_5 = "'Keep_selected' < 1'
    temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
    arcpy.management.DeleteRows(temp_select5)

# save selected edges (solution)
solution = len(selected_edges)
selected_edges[solution] = []

with arcpy.da.SearchCursor(adjacent_edges, ["ID"]) as cur_11:
    for row_11 in cur_11:
        selected_edges[solution].append(row_11[0])

# prepare file for network dataset
selected_rail_edges = new_network_location + "/" + new_rail_edges

return bttest9, bttest8, bttest7, bttest6, bttest5, bttest4, bttest3, bttest2, bttest1

```



```

def local_search_remove(out_path, new_rail_edges_path, selected_rail_edges, new_rail_edges,
new_network_location, selected_edges, used_new_rail_edges, minimum_edge_volume):

    try:
        arcpy.management.Delete(selected_rail_edges)
    except Exception:
        e = sys.exc_info()[1]
        print(e.args[0])

    # find used new rail edges
    Type = "Domestic"
    used_new_rail_edges_domestic = arcpy.management.CreateTable(out_path, "used_new_rail_edges_domestic")
    where_clause_2 = "RouteType" + " = " + Type + ""
    temp_select2 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges, 'NEW_SELECTION',
where_clause_2)
    arcpy.management.CopyRows(temp_select2, used_new_rail_edges_domestic)

    # alter SUM_vol_total name, so is different from the field in selected_rail_edges (initial solution volume)
    try:
        arcpy.management.AlterField(used_new_rail_edges_domestic, "SUM_vol_total", "best_solution_volume",
"best_solution_volume")
    except Exception:
        e = sys.exc_info()[1]
        print(e.args[0])

    # remove low values
    where_clause_3 = "best_solution_volume" + " < " + str(minimum_edge_volume)
    temp_select3 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges_domestic,
'NEW_SELECTION', where_clause_3)
    arcpy.management.DeleteRows(temp_select3)

    # create Feature Class with adjacent edges
    arcpy.conversion.FeatureClassToGeodatabase(new_rail_edges_path, new_network_location)
    adjacent_edges = new_network_location + "/" + new_rail_edges
    arcpy.management.AddIndex(adjacent_edges, ["ID"], "Index2", "UNIQUE", "ASCENDING")

    # add best solution volume to selected_rail_edges
    arcpy.management.AddIndex(used_new_rail_edges_domestic, ["SourceOID"], "Index2", "UNIQUE",
"ASCENDING")
    arcpy.management.JoinField(adjacent_edges, "ID", used_new_rail_edges_domestic, "SourceOID",
["best_solution_volume"])

    # remove null values - keep only used edges with volume higher than minimum
    where_clause_4 = "best_solution_volume" is null'
    temp_select4 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_4)
    arcpy.management.DeleteRows(temp_select4)

    # save selected edges (solution)
    solution = len(selected_edges)
    selected_edges[solution] = []

    with arcpy.da.SearchCursor(adjacent_edges, ["ID"]) as cur_11:
        for row_11 in cur_11:
            selected_edges[solution].append(row_11[0])

    # prepare file for network dataset
    selected_rail_edges = new_network_location + "/" + new_rail_edges

```

```

def local_search_top5(out_path, new_rail_edges_path, selected_rail_edges, new_rail_edges, new_network_location,
count, selected_edges, used_new_rail_edges, test9, test8, test7, test6, test5, test4, test3, test2, test1,
minimum_edge_volume, lower_bound, Solution_Nb):

    # create Feature Class with current solution selected edges
    if(count==0):
        try:
            arcpy.management.Delete(selected_rail_edges)
        except Exception:
            e = sys.exc_info()[1]
            print(e.args[0])
        arcpy.conversion.FeatureClassToGeodatabase(new_rail_edges_path, out_path)
        selected_rail_edges = out_path + "/" + new_rail_edges

        # find used new rail edges
        Type = "Domestic"
        used_new_rail_edges_domestic = arcpy.management.CreateTable(out_path, "used_new_rail_edges_domestic")
        where_clause_2 = "'RouteType' = '" + Type + "'"
        temp_select2 = arcpy.management.SelectLayerByAttribute(used_new_rail_edges, 'NEW_SELECTION',
where_clause_2)
        arcpy.management.CopyRows(temp_select2, used_new_rail_edges_domestic)

        # alter SUM_vol_total name, so is different from the field in selected_rail_edges (initial solution volume)
        try:
            arcpy.management.AlterField(used_new_rail_edges_domestic, "SUM_vol_total", "best_solution_volume",
"best_solution_volume")
        except Exception:
            e = sys.exc_info()[1]
            print(e.args[0])

        # add best solution volume to selected_rail_edges
        arcpy.management.AddIndex(used_new_rail_edges_domestic, ["SourceOID"], "Index2", "UNIQUE",
"ASCENDING")
        arcpy.management.JoinField(selected_rail_edges, "ID", used_new_rail_edges_domestic, "SourceOID",
["best_solution_volume"])

        # remove null values
        where_clause_3 = "'best_solution_volume' is null"
        temp_select3 = arcpy.management.SelectLayerByAttribute(selected_rail_edges, 'NEW_SELECTION',
where_clause_3)
        arcpy.management.CalculateField(temp_select3, "best_solution_volume", 0)
        arcpy.management.SelectLayerByAttribute(selected_rail_edges, 'CLEAR_SELECTION')

        # find selected rail edges
        solution_size = len(selected_edges[Solution_Nb])
        arcpy.management.CalculateField(selected_rail_edges, "Keep", 0, field_type="SHORT")

        with arcpy.da.UpdateCursor(selected_rail_edges, ["ID", "Keep"]) as cur_a:
            for row_a in cur_a:
                for k in range(0, solution_size, 1):
                    if(selected_edges[Solution_Nb][k] == row_a[0]):
                        row_a[1] = 1
                        cur_a.updateRow(row_a)
                        break

        where_clause_4 = "'Keep' = 0"
        temp_select4 = arcpy.management.SelectLayerByAttribute(selected_rail_edges, 'NEW_SELECTION',
where_clause_4)
        arcpy.management.DeleteRows(temp_select4)

        # create Feature Class with adjacent edges
        arcpy.conversion.FeatureClassToGeodatabase(new_rail_edges_path, new_network_location)

```

```

adjacent_edges = new_network_location + "/" + new_rail_edges
arcpy.management.AddIndex(adjacent_edges, ["ID"], "Index2", "UNIQUE", "ASCENDING")
arcpy.management.CalculateField(adjacent_edges, "Keep_used", 0, field_type="SHORT")
arcpy.management.CalculateField(adjacent_edges, "Keep_selected", 0, field_type="SHORT")

# prepare the iteration
test9 = 0
test8 = 0
test7 = 0
test6 = 0
test5 = 0
test4 = 0
test3 = 0
test2 = 0
test1 = 0

# find and insert adjacent edges
with arcpy.da.UpdateCursor(adjacent_edges, ["ID", "StartPtID", "EndPtID", "Keep_used", "SUM_vol_total",
"Keep_selected"]) as cur_c:
    for row_c in cur_c:
        with arcpy.da.SearchCursor(selected_rail_edges, ["ID", "StartPtID", "EndPtID",
"best_solution_volume"]) as cur_d:
            for row_d in cur_d:
                # selected new rail edges
                if(row_c[0]==row_d[0]):
                    # remove selected, not used
                    if(row_d[3]==0):
                        row_c[3] = 5
                        row_c[5] = 5
                        cur_c.updateRow(row_c)
                        # if there is no chance in improving "keep" value, break
                        break
                    # remove used, but with volume lower than minimum
                    elif(row_d[3]<minimum_edge_volume):
                        row_c[3] = 10
                        row_c[5] = 10
                        cur_c.updateRow(row_c)
                        # if there is no chance in improving "keep" value, break
                        break
                    # keep used with volume higher than minimum
                    elif(row_d[3]>=minimum_edge_volume):
                        row_c[3] = 11
                        row_c[5] = 11
                        cur_c.updateRow(row_c)
                        # if there is no chance in improving "keep" value, break
                        break
                # add adjacent edges with high initial volume to used new rail edges
                if(row_c[0]!=row_d[0] and ((row_c[1]==row_d[1] or row_c[1]==row_d[2]) or (row_c[2]==row_d[1]
or row_c[2]==row_d[2])) and row_d[3]>0):
                    # adjacent edge with chance to improve "keep" value and with initial volume greater than 90% of
lower_bound
                    if((row_c[3]<9) and (row_c[4]>=0.9*lower_bound)):
                        row_c[3] = 9
                        cur_c.updateRow(row_c)
                    # adjacent edge with chance to improve "keep" value and with initial volume greater than 80% of
lower_bound
                    elif((row_c[3]<8) and (row_c[4]<0.9*lower_bound and row_c[4]>=0.8*lower_bound)):
                        row_c[3] = 8
                        cur_c.updateRow(row_c)
                    # adjacent edge with chance to improve "keep" value and with initial volume greater than 70% of
lower_bound
                    elif((row_c[3]<7) and (row_c[4]<0.8*lower_bound and row_c[4]>=0.7*lower_bound)):

```

```

        row_c[3] = 7
        cur_c.updateRow(row_c)
        # adjacent edge with chance to improve "keep" value and with initial volume greater than
minimum_edge_volume
        elif((row_c[3]<6) and (row_c[4]<0.7*lower_bound and row_c[4]>=minimum_edge_volume)):
            row_c[3] = 6
            cur_c.updateRow(row_c)
            # add adjacent edges with high initial volume to selected new rail edges
            if(row_c[0]!=row_d[0] and ((row_c[1]==row_d[1] or row_c[1]==row_d[2]) or (row_c[2]==row_d[1]
or row_c[2]==row_d[2])) and row_d[3]>=0):
                # adjacent edge with chance to improve "keep" value and with initial volume greater than 90% of
lower_bound
                if((row_c[5]<4) and (row_c[4]>=0.9*lower_bound)):
                    row_c[5] = 4
                    cur_c.updateRow(row_c)
                    # adjacent edge with chance to improve "keep" value and with initial volume greater than 80% of
lower_bound
                    elif((row_c[5]<3) and (row_c[4]<0.9*lower_bound and row_c[4]>=0.8*lower_bound)):
                        row_c[5] = 3
                        cur_c.updateRow(row_c)
                        # adjacent edge with chance to improve "keep" value and with initial volume greater than 70% of
lower_bound
                        elif((row_c[5]<2) and (row_c[4]<0.8*lower_bound and row_c[4]>=0.7*lower_bound)):
                            row_c[5] = 2
                            cur_c.updateRow(row_c)
                            # adjacent edge with chance to improve "keep" value and with initial volume greater than
minimum_edge_volume
                            elif((row_c[5]<1) and (row_c[4]<0.7*lower_bound and row_c[4]>=minimum_edge_volume)):
                                row_c[5] = 1
                                cur_c.updateRow(row_c)

# update test variables
where_clause_1 = "Keep_used" <> 0'
temp_select1 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_1)

with arcpy.da.SearchCursor(temp_select1, ["Keep_used"]) as cur_a:
    for row_a in cur_a:
        if(row_a[0]==9):
            test9 += 1
        elif(row_a[0]==8):
            test8 += 1
        elif(row_a[0]==7):
            test7 += 1
        elif(row_a[0]==6):
            test6 += 1
        elif(row_a[0]==5):
            test5 += 1

where_clause_1 = "Keep_selected" <> 0'
temp_select1 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_1)

with arcpy.da.SearchCursor(temp_select1, ["Keep_selected"]) as cur_a:
    for row_a in cur_a:
        if(row_a[0]==4):
            test4 += 1
        elif(row_a[0]==3):
            test3 += 1
        elif(row_a[0]==2):
            test2 += 1
        elif(row_a[0]==1):

```

```

        test1 += 1

# copy adjacent edges to out_path - store for next iterations
arcpy.conversion.FeatureClassToGeodatabase(adjacent_edges, out_path)
arcpy.conversion.TableToExcel(adjacent_edges, "adjacent_edges" + str(len(selected_edges)) + ".xlsx")

elif(count>0):
    try:
        arcpy.management.Delete(selected_rail_edges)
    except Exception:
        e = sys.exc_info()[1]
        print(e.args[0])

# create Feature Class with adjacent edges - with "keep" information from count = 0
adjacent_edges = out_path + "/" + new_rail_edges
arcpy.conversion.FeatureClassToGeodatabase(adjacent_edges, new_network_location)
adjacent_edges = new_network_location + "/" + new_rail_edges

if(count==0):
    # keep used edges and adjacent edges with high initial value
    if(test9 > 0):
        where_clause_5 = "'Keep_used' < 9'"
    elif(test8 > 0):
        where_clause_5 = "'Keep_used' < 8'"
    elif(test7 > 0):
        where_clause_5 = "'Keep_used' < 7'"
    else:
        where_clause_5 = "'Keep_used' < 6'"
    temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
    arcpy.management.DeleteRows(temp_select5)
elif(count==1):
    # keep used edges and adjacent edges with high initial value
    if(test9 > 0 and test8 > 0):
        where_clause_5 = "'Keep_used' < 8'"
    elif((test9 > 0 or test8 > 0) and test7 > 0):
        where_clause_5 = "'Keep_used' < 7'"
    else:
        where_clause_5 = "'Keep_used' < 6'"
    temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
    arcpy.management.DeleteRows(temp_select5)
elif(count==2):
    # keep selected edges and adjacent edges with high initial value
    if(test4 > 0):
        where_clause_5 = "'Keep_selected' < 4'"
    elif(test3 > 0):
        where_clause_5 = "'Keep_selected' < 3'"
    elif(test2 > 0):
        where_clause_5 = "'Keep_selected' < 2'"
    else:
        where_clause_5 = "'Keep_selected' < 1'"
    temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
    arcpy.management.DeleteRows(temp_select5)
elif(count==3):
    # keep selected edges and adjacent edges with high initial value
    if(test4 > 0 and test3 > 0):
        where_clause_5 = "'Keep_selected' < 3'"
    elif((test4 > 0 or test3 > 0) and test2 > 0):
        where_clause_5 = "'Keep_selected' < 2'"
    else:

```

```
        where_clause_5 = "Keep_selected" < 1'
    temp_select5 = arcpy.management.SelectLayerByAttribute(adjacent_edges, 'NEW_SELECTION',
where_clause_5)
    arcpy.management.DeleteRows(temp_select5)

# save selected edges (solution)
solution = len(selected_edges)
selected_edges[solution] = []

with arcpy.da.SearchCursor(adjacent_edges, ["ID"]) as cur_11:
    for row_11 in cur_11:
        selected_edges[solution].append(row_11[0])

# prepare file for network dataset
selected_rail_edges = new_network_location + "/" + new_rail_edges

return test9, test8, test7, test6, test5, test4, test3, test2, test1
```

APPENDIX C. Code for the Brazil's agricultural products logistic network improvement model.

```
$ONECHO > PARAMETROS.TXT
```

```
*Sets
```

```
set=o      rng=sets!a2:a1000000 RDIM=1
set=d      rng=sets!c2:c1000000 RDIM=1
set=j      rng=sets!i2:i1000000 RDIM=1
set=e      rng=sets!k2:k1000000 RDIM=1
set=m      rng=sets!m2:m1000000 RDIM=1
set=i      rng=sets!o2:o1000000 RDIM=1
set=p      rng=sets!q2:q1000000 RDIM=1
```

```
*Subsets
```

```
set=orj    rng=combin!a2:c10000000 RDIM=3
```

```
*Supply and demand parameters
```

```
par=ofm    rng=oferta!a1 CDIM=1 RDIM=2
par=demm   rng=demanda!a1 CDIM=1 RDIM=2
par=dme    rng=export!a1 CDIM=1 RDIM=2
par=oim    rng=import!aa1 CDIM=1 RDIM=2
```

```
*Freight and product price parameters
```

```
par=pfoj   rng=fretes!a1:e1000000 RDIM=4
par=pfjd   rng=fretes!g1:k1000000 RDIM=4
par=pfje   rng=fretes!m1:q1000000 RDIM=4
par=pfod   rng=fretes!s1:w1000000 RDIM=4
par=pfoe   rng=fretes!y1:ac1000000 RDIM=4
par=pfid   rng=fretes!ae1:ai1000000 RDIM=4

par=pmo    rng=precoprodola1 RDIM=2 CDIM=1
par=pmj    rng=precoprodj!a1 RDIM=2 CDIM=1
par=pmi    rng=precoprodila1 RDIM=2 CDIM=1
```

```
*Storage parameters
```

```
par=cam    rng=armazem!n1:o1000000 RDIM=1
par=crb    rng=armazem!q1:r1000000 RDIM=1

par=cpe    rng=armazem!b1:c1000000 RDIM=1
par=eij    rng=armazem!t1:v1000000 RDIM=2
```

```
*Taxes parameters
```

```
par=ipmjd  rng=impostos!b2:e2000000 RDIM=3
par=ipmod  rng=impostos!h2:k2000000 RDIM=3
```

```
*CO2 emissions parameters
```

```
par=emoj   rng=emissoes!a1:c1000000 RDIM=2
par=emjd   rng=emissoes!e1:g1000000 RDIM=2
par=emje   rng=emissoes!i1:k1000000 RDIM=2
par=emod   rng=emissoes!m1:o1000000 RDIM=2
par=emoe   rng=emissoes!q1:s1000000 RDIM=2
par=emid   rng=emissoes!u1:w1000000 RDIM=2
```

```
$OFFECHO
```

```
$CALL GDXRW.EXE infra_2035.xlsx @PARAMETROS.TXT
$GDXIN infra_2035.GDX
```

```
Sets
```

```
* Sets
```

o Origins (producing areas)
 d Destinations (demand points)
 e Exporting ports
 m Months
 j Warehouses points
 i Entry points
 p Products

* Subsets

orj(p,o,j) subset of the combinations between origins and warehouses (only in the same state) ;

\$LOAD o d e m j i p orj

Parameters

*Supply and demand parameters

ofm(p,o,m) total supply volume by origin o for product p on month m (in tonnes of cargo)
 demm(p,d,m) total demanded volume by destination d for product p on month m (in tonnes of cargo)
 dme(p,e,m) total exported volume by exporting port e for product p on month m (in tonnes of cargo)
 oim(p,i,m) maximum imported volume by entry point i for product p on month m (in tonnes of cargo)

*Freight and product price parameters

pfoj(p,o,j,m) freight cost from origin o to warehouse j for product p on month m (in R\$ per tonne of cargo)
 pfjd(p,j,d,m) freight cost from warehouse j to destination d for product p on month m (in R\$ per tonne of cargo)
 pfje(p,j,e,m) freight cost from warehouse j to exporting port e for product p on month m (in R\$ per tonne of cargo)
 pfod(p,o,d,m) freight cost from origin o to destination d for product p on month m (in R\$ per tonne of cargo)
 pfoe(p,o,e,m) freight cost from origin o to exporting port e for product p on month m (in R\$ per tonne of cargo)
 pfid(p,i,d,m) freight cost from entry point i to destination d for product p on month m (in R\$ per tonne of cargo)

pmj(p,j,m) price of product p in warehouse j on month m (in R\$ per tonne of cargo)
 pmo(p,o,m) price of product p in origin o on month m (in R\$ per tonne of cargo)
 pmi(p,i,m) price of product p in entry point i on month m (in R\$ per tonne of cargo)

cam(j) monthly storage fee of warehouse j (in R\$ per tonne of cargo)
 crb(j) storage handling and drying fee of warehouse j (in R\$ per tonne of cargo)

*Storage capacity parameters

cpe(j) maximum storage capacity of warehouse j (in tonnes of cargo)
 eij(p,j) initial stored volume of product p in warehouse j (in tonnes of cargo)

*CO2 emissions parameters

emoj(o,j) CO2 emission rate from origin o to warehouse j (in kgCO2 per tonne of cargo)
 emjd(j,d) CO2 emission rate from warehouse j to destination d (in kgCO2 per tonne of cargo)
 emje(j,e) CO2 emission rate from warehouse j to exporting port e (in kgCO2 per tonne of cargo)
 emod(o,d) CO2 emission rate from origin o to destination d (in kgCO2 per tonne of cargo)
 emoe(o,e) CO2 emission rate from origin o to exporting port e (in kgCO2 per tonne of cargo)
 emid(i,d) CO2 emission rate from entry point i to destination d (in kgCO2 per tonne of cargo)

* Taxes parameters

ipmjd(p,j,d) taxes on price of product p from warehouse j to destination d (in %)
 ipmod(p,o,d) taxes on price of product p from origin o to destination d (in %) ;

\$LOAD ofm demm dme oim pfoj pfjd pfje pfod pfoe pfid pmo pmj pmi cam crb cpe eij ipmjd ipmod emoj emjd
 emje emod emoe emid
 \$GDXIN

Scalar

txi / 0 /
 alfa / 1 /
 beta / 15 /
 transbordo / 0 /;

Variables

*total costs and CO2 emissions

z objective function - total annual costs and CO2 emissions

*Costs

cj monthly storage cost

coj logistic cost and CO2 emissions between origin and warehouse

cjd logistic cost and CO2 emissions between warehouse and destination

cje logistic cost and CO2 emissions between warehouse and exporting ports

cod logistic cost and CO2 emissions between origin and destination

coe logistic cost and CO2 emissions between origin and exporting ports

cid logistic cost and CO2 emissions between entry point and destination

*Flows - from Origins

oj(p,o,j,m) volume transported between origin and warehouse

od(p,o,d,m) volume transported between origin and destination

oe(p,o,e,m) volume transported between origin and exporting ports

*Flows - from Warehouses

jd(p,j,d,m) volume transported between warehouse and destination

je(p,j,e,m) volume transported between warehouse and exporting ports

*Fluxos - From Entry points

id(p,i,d,m) volume transported between entry point and destination

*Storage variables

estj(p,j,m) volume stored of product p in warehouse j in month m

compj(j) increase of static storage capacity volume of warehouse j;

Positive Variables estj, oj, od, oe, jd, je, id, coj, cod, coe, cjd, cje, cid, cj, compj;

Equations

fobjt objective function - total annual costs and CO2 emissions

vest monthly storage cost

voj logistic cost and CO2 emissions between origin and warehouse

vod logistic cost and CO2 emissions between origin and destination

voe logistic cost and CO2 emissions between origin and exporting ports

vjd logistic cost and CO2 emissions between warehouse and destination

vje logistic cost and CO2 emissions between warehouse and exporting ports

import logistic cost and CO2 emissions between entry point and destination

oferta(p,o,m) constraint - supply volume by origin o for product p on month m

demandad(p,d,m) constraint - demanded volume by destination d for product p on month m

demandae(p,e,m) constraint - exported volume by exporting port e for product p on month m

ofertai(p,i,m) constraint - imported volume by entry point i for product p on month m

ccomp constraint - total increase of static storage capacity volume

estoqueji(p,j,m) constraint - monthly stored volume - month 1

estoquejf(p,j,m) constraint - monthly stored volume - month 2 to 12

capestoq(j,m) constraint - monthly capacity by warehouse ;

*objective function - total annual costs and CO2 emissions

fobjt.. $z = e = cj + coj + cjd + cje + cod + coe + cid ;$

*Cost equations

vest.. $cj = e = \sum((p,j,m), estj(p,j,m)*cam(j)*alfa);$ voj.. $coj = e = \sum((p,o,j,m), oj(p,o,j,m)*\$orj(p,o,j)*pfoj(p,o,j,m)*alfa) + \sum((p,o,j,m),$ $oj(p,o,j,m)*\$orj(p,o,j)*crb(j)*alfa) + \sum((p,o,j,m), oj(p,o,j,m)*\$orj(p,o,j)*emoj(o,j)*beta);$ vjd.. $cjd = e = \sum((p,j,d,m), jd(p,j,d,m)*pfjd(p,j,d,m)*alfa) +$ $\sum((p,j,d,m), jd(p,j,d,m)*pmj(p,j,m)*(1+ipmjd(p,j,d))*alfa) + \sum((p,j,d,m), jd(p,j,d,m)*emjd(j,d)*beta) ;$

vje.. cje =e= sum((p,j,e,m), je(p,j,e,m)*pfje(p,j,e,m)*alfa) + sum((p,j,e,m),je(p,j,e,m)*pmj(p,j,m)*alfa) +
sum((p,j,e,m), je(p,j,e,m)*emje(j,e)*beta);

vod.. cod =e= sum((p,o,d,m), od(p,o,d,m)*pfod(p,o,d,m)*alfa) +
sum((p,o,d,m),od(p,o,d,m)*pmo(p,o,m)*(1+ipmod(p,o,d))*alfa) + sum((p,o,d,m), od(p,o,d,m)*emod(o,d)*beta);

voe.. coe =e= sum((p,o,e,m), oe(p,o,e,m)*pfoe(p,o,e,m)*alfa) +
sum((p,o,e,m),oe(p,o,e,m)*pmo(p,o,m)*alfa) + sum((p,o,e,m), oe(p,o,e,m)*emoe(o,e)*beta);

import.. cid =e= sum((p,i,d,m), id(p,i,d,m)*pfid(p,i,d,m)*alfa) + sum((p,i,d,m),id(p,i,d,m)*pmi(p,i,m)/(1-
txi)*alfa) + sum((p,i,d,m), id(p,i,d,m)*emid(i,d)*beta);

*Supply and demand equations

demandae(p,e,m).. sum((o), oe(p,o,e,m)) + sum((j), je(p,j,e,m)) =e= dme(p,e,m) ;

oferta(p,o,m).. sum((j), oj(p,o,j,m)\$orj(p,o,j)) + sum((e), oe(p,o,e,m)) + sum((d), od(p,o,d,m)) =e=
ofm(p,o,m) ;

demandad(p,d,m).. sum((o), od(p,o,d,m)) + sum((j), jd(p,j,d,m)) + sum((i), id(p,i,d,m)) =e= demm(p,d,m) ;

ofertai(p,i,m).. sum((d), id(p,i,d,m)) =l= oim(p,i,m) ;

*Storage equations

ccomp.. sum((j), compj(j)) =g= 0;

estoqueji(p,j,m)\$ (ORD(m) eq 1).. estj(p,j,m) =e= cij(p,j)+sum((o), oj(p,o,j,m)\$orj(p,o,j))-sum((d), jd(p,j,d,m)) -
sum((e), je(p,j,e,m));

estoquejf(p,j,m)\$ (ORD(m) ge 2).. estj(p,j,m) =e= estj(p,j,m-1)+sum((o), oj(p,o,j,m)\$orj(p,o,j))-sum((d),
jd(p,j,d,m)) - sum((e), je(p,j,e,m));

capestoq(j,m).. sum((p), estj(p,j,m)) =l= cpe(j) + compj(j);

Model transport /all/;

Solve transport using LP minimizing z;

DISPLAY z.L, estj.L, oj.L, od.L, oe.L, jd.L, je.L, id.L, cj.L, coj.L, cjd.L, cje.L, cod.L, coe.L, cid.L, compj.L ;

execute_unload "r_infra_2035_result.gdx" z.L, estj.L, oj.L, od.L, oe.L, jd.L, je.L, id.L, cj.L, coj.L, cjd.L, cje.L, cod.L,
coe.L, cid.L,
compj.L ;

execute 'gdxxrw.exe r_infra_2035_result.gdx var=compj.L rng=compensatorio!b2:c10000000 rdim=1';

execute 'gdxxrw.exe r_infra_2035_result.gdx var=estj.L rng=estoques!a2:e10000000 rdim=3';

execute 'gdxxrw.exe r_infra_2035_result.gdx var=oj.L rng=custosoj!a2:e10000000 rdim=4';

execute 'gdxxrw.exe r_infra_2035_result.gdx var=je.L rng=custosje!a2:e10000000 rdim=4';

execute 'gdxxrw.exe r_infra_2035_result.gdx var=jd.L rng=custosjd!a2:e10000000 rdim=4';

execute 'gdxxrw.exe r_infra_2035_result.gdx var=od.L rng=custosod!a2:e10000000 rdim=4';

execute 'gdxxrw.exe r_infra_2035_result.gdx var=oe.L rng=custosoe!a2:e10000000 rdim=4';

execute 'gdxxrw.exe r_infra_2035_result.gdx var=id.L rng=custosid!a2:e10000000 rdim=4';

execute 'gdxxrw.exe r_infra_2035_result.gdx var=z.L rng=custos!a1 rdim=0';

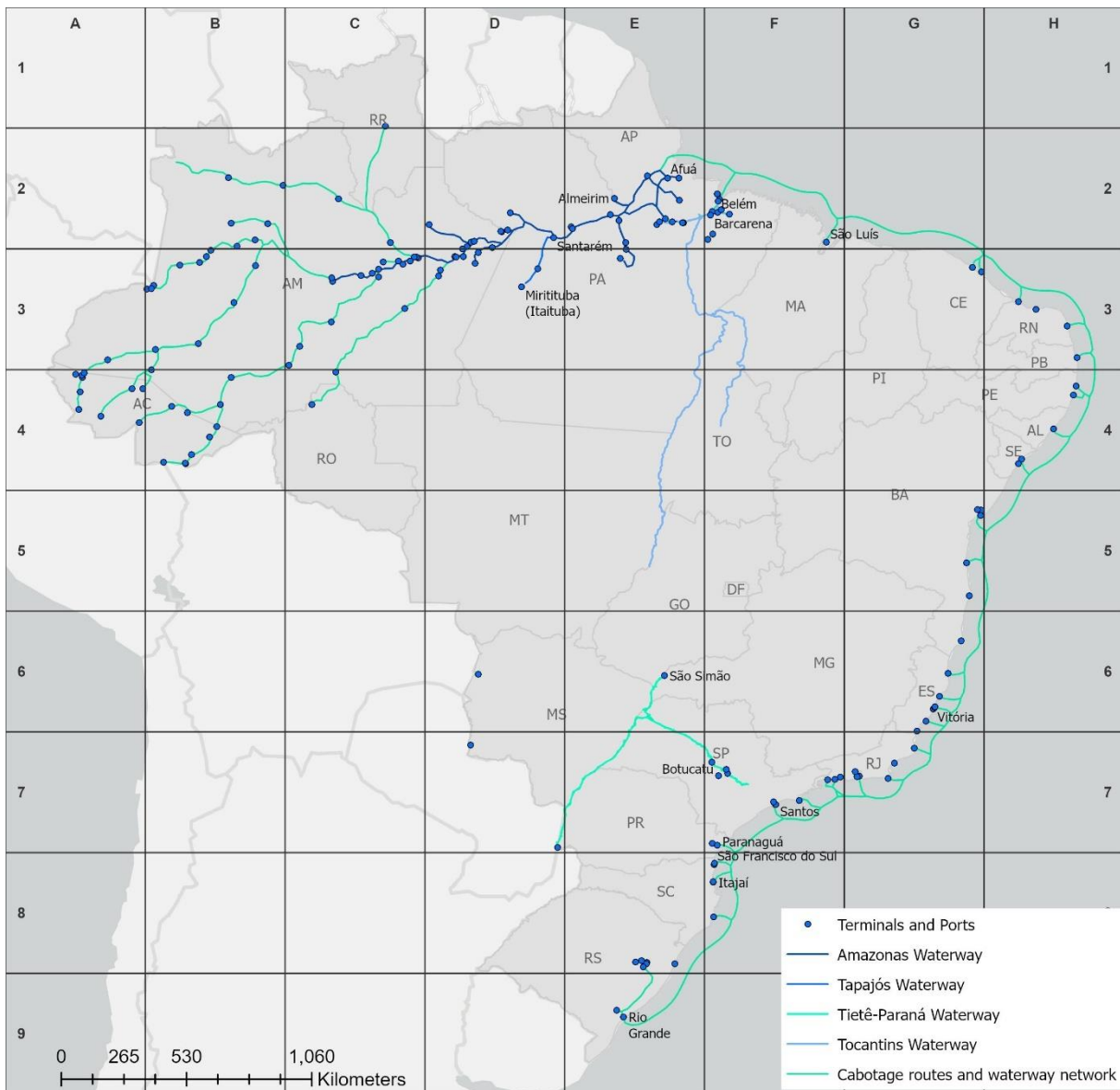
ANNEXES

ANNEX A. Brazil's main railways, ports, and cities.



Sources: EPL (2021c) and IBGE (2022a).

ANNEX B. Brazil's 2035 expected cabotage routes, waterway network, ports, and terminals.



Sources: EPL (2021c) and IBGE (2022a).