A Decision Support Tool for Strategic Planning of Multimodal Transport Infrastructure

The Case of Brazil

MSc. Transport, Infrastructure and Logistics

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by

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Preface

This thesis is the final product of the Master of Science program 'Transport, Infrastructure and Logistics' at the Delft University of Technology. It describes the main impacts of railway infrastructure investments in Brazil, a continent-sized country, where transport of cargo plays a leading role in reducing transportation costs. The decision to follow this Master program is a result of my drive to enable Brazil to become a more competitive country by achieving a more even structure of the cargo transport matrix. My hope is that I was able to give one step forward in the challenging task of promoting railway transportation in Brazil, and it is my sincere wish that the results obtained in this research are found to be valuable.

I would like to express my gratitude to my supervising committee, as their support definitely has steepened my learning curve during this research trajectory. My sincere gratitude goes to Lóri Tavasszy, whom I admire for his deep concern in preparing students for their careers. To Yousef Maknoon, for patiently sharing his extensive knowledge with me and challenging me to always go a step further in my research. To Bilge Atasoy for the great assistance and willingness to help throughout this journey. Lastly, to Wouter Demenint, who has acted not only as my supervisor, but also as a great friend. I can't thank you enough for all your words of support and for your trust on my work.

I feel blessed for having had the opportunity of conducting this research together with the Port of Rotterdam, and for having met so many great people during this journey. I wanna thank the whole Port of Rotterdam International team for welcoming me into their team, for all the nice chats at the office and for the words of support. Additionally, I want to specifically thank Yorian van Leeuwen, Aiara Lobo Gomes and David Fortini for assisting me with all programming challenges I have faced during this journey. Without your time, knowledge and patience I would not have achieved so much.

Lastly, I am extremely thankful to my family and friends. My family, who spared no efforts to support me! My gratitude goes to them, who always believed in my potential and encouraged me to keep going after my dreams. To my boyfriend Olivier Benz, who has been my anchor during this whole master journey. And of course, to all friends that have accompanied me throughout my journey and made this master journey more pleasant.

I can only be thankful for all great people that have supported me throughout this journey!

R. van den Boogaard
Delft, December 2019

Summary

The transport of freight with the use of at least two modes of transport is known as multimodal freight transportation. The planning of multimodal transport infrastructure is a rather complex process. *Network planners* (i.e. government, policy makers) have to make use of governments limited budgets to improve the network while considering the *network user's* (i.e. land and shipping companies) motivation of minimizing the total costs of transportation. Additionally, research has highlighted the need of encompassing all dimensions of sustainable transport goals into transport models (i.e. CO_e emissions, transport times, modal share). Even though the Multimodal Network Design Problems (MNDP) deal with the aforementioned topic, the complexity of such algorithms and long computational times have hindered it' s use. Thus, the goal of this thesis is to develop a *Decision Support Tool* to assist network planners in strategically planning multimodal transport infrastructure while overcoming the difficulties of the MNDP. To achieve this goal the following research question was formulated:

What Decision Support Tool can be used to assist network planners in the policy-making decisions for multimodal transport infrastructures?

To achieve this goal a *Decision Support Tool for the Strategical Planning of Multimodal Transport Infrastrcture* was developed and validated with a *Case Study* for the Brazilian Freight Transport Network. The developed tool is presented in Figure 1, followed by a brief description of the several distinguishable steps.

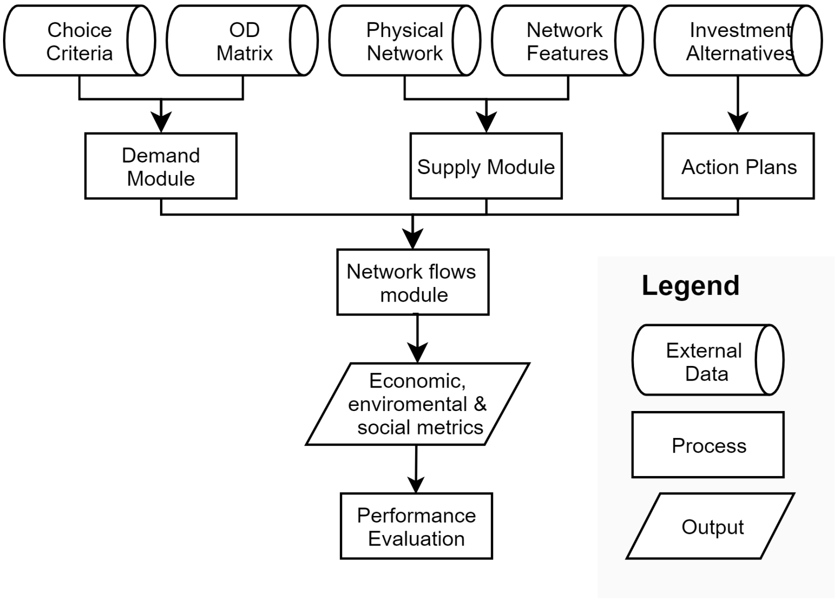

Figure 1: Decision Support Tool for the Strategic Planning of Multimodal Transport Infrastructure

1. Demand Module: this steps consists of the aggregation of data regarding transport demand into origin-destination (O-D) matrices and the definition of the main choice criteria of *network users* when choosing for a route on a multimodal network.
2. Supply Module: this step consists of the generation of a supernetwork, including the physical network of road, rail and water segments, the transfer network and the origin-destination nodes. Supernetworks are networks that allow for the simultaneous choice of mode and route by *network users*, with the inclusion of transfer points.
3. Action Plans: during this step an analysis of the problem takes place and the main project alternatives considered by the *network planner* are presented. Project alternatives can include the establishment of new infrastructure segments, the improvement of existing ones and even new policy regulations.

4. Network Flow Module: this model calculates the flows in the network with the use of a k-shortest-paths algorithm. The choice probabilities of paths are calculated from the utility maximization perspective of the *network users*, and additional paths are added to the route set until one of the paths violates the pre-defined probability constraint. Once all possible routes are generated, cargo flows are distributed over the network. The process is individually repeated for all of the proposed *Action Plans*.

5. Performance Evaluation: the last step of the developed tool consists of the evaluation of the obtained outputs, and comparison of the performance of different alternatives. The results are analyzed in terms of economic, environmental and social impacts. Pareto Frontiers, Benefit Cost Rations and analysis of all metrics of each *Action Plan* are used for the comparison of their performance.

The validity of the tool has been tested for the Case of Brazil. The input data for the model was obtained from several government databases. The data used in the demand module was obtained from EPL (2018a), and the transport demand has been aggregated into 48 zones. The supply module included the physical infrastructure of roads, rails and waterways. Travel times and distances between zones by road were retrieved with the use of the Google API application. The railway network was aggregated with the use of data obtained from *ANTF* (2019). Next, port clusters were defined and waterway links created between them and choice behavior coefficients were obtained from a stated-choice experiment conducted by EPL (2018a).

As the railway network of in Brazil is extremely scarce and several investments are required to foster the use of the mode, *Action Plans* have been built based on changes in the railway network. This included the establishment of new rail segments, as well as different speeds of operations for the rail mode. To test the reliability of the model, a *Face Validation* session took place. The model was tested for the transport demand of 2015. Port throughput's of the model were compared with the ANTAQ (2019) database, and the modal share of roadways and railways were compared with the ones provided by *ANTF* (2019). This results were presented to two experts at the Port of Rotterdam, and were considered to be consistent with the real cargo flows in Brazil. This results have shown the model capacity of replicating the behavior of network users on an aggregated level. Following the impacts of the proposed *Action Plans* was measured in terms of economic, environmental and social impacts. Results have shown the potential cargo flows that can be attracted attracted by new railway connections,and the changes in time, cost and CO_2 emissions on the whole network.

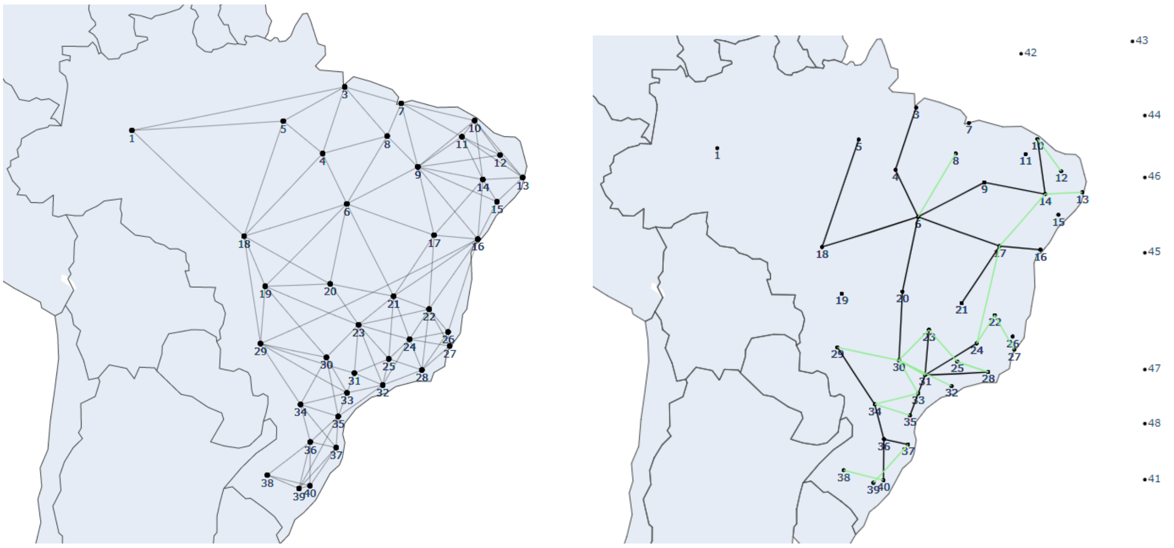

Figure 2: Aggregated Roadway Network

Figure 3: Port Clusters and Railway Network

Figure 4: Supply Networks

The Action Plans have been tested under consideration of operation speeds of 28 km/h, 50 km/h, 100 km/h and 150 km/h. Investments costs were considered to be 7 mi R$/km for standard railways and 25 R$/km for medium speed railways (150 km/h according to *ANTF* (2019). With the calculation of benefit cost ratio for each of the Action Plans, results have shown that with the given investment costs BCR for the investments in a 150 km/h railway are much higher than for the other alternatives. Following, Action Plans 7, 26, 3 and

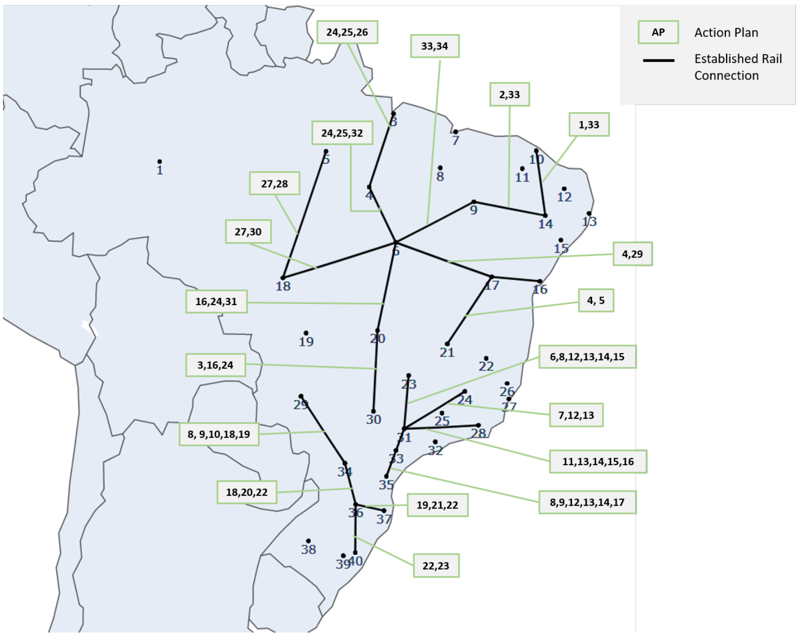

Figure 5: Proposed Action Plans

32 have proven to be the best options in terms of economic benefits. The results have also shown the trade-offs made by *network users* in terms of cost and time savings. For the establishment of railway connections with short distances, the model has shown that railways do not present enough benefits for network users to switch from the road mode. Likewise, results have shown the difficult of cargo attraction for railways located in zones where demands are low. Lastly, it could be observed that *network users* make a trade-off between costs and travel times, and that the increase in railway speeds results in higher flows on railway connections. From an environmental perspective results have shown that Action Plans 7, 2 and 32 are the ones with the best trade-off between investment costs and reductions in CO_2 emissions. From a social perspective results indicated that the more investments are made on the railway network, the higher the modal share of the railways.

The results of the model suggest that the establishment of new railway connections and increases in speed can reduce the total costs and environmental footprint of transportation over the network. Finally, according to the model assumptions, it was concluded network users have a preference towards faster railway services. Finally, the model has proven to be able to quantify the economic, environmental and social impacts of the proposed action plans over the full network, while presenting solid and reliable results.

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Abbreviations

NP-hard	Non-deterministic Polynomial-time Hardness
MNDP	Multimodal Network Design Problem
MNL	Multimodal Logit Model
BCR	Benefit Cost Ratio
RC	Reference Case
VoT	Value of Time
ANTAQ	Agência Nacional de Tranportes Aquaviários
ANTF	Agência Nacional de Tranporte Ferroviário
PNL	Plano Nacional de Logística
EPL	Empresa Nacional de Logística
ANTT	Agência Nacional de Tranporte Terrestre
OD	Origin-Destination
AP	Action Plan

1

Introduction

In this chapter the purpose and content of the thesis are discussed. Background information regarding multimodal freight flows is provided, followed by the problem statement.

1.1. Problem Definition

In this research we look into the problem of planning freight transport infrastructure investments for multimodal networks. Multimodal freight transportation consists of the use of at least two modes of transportation, such as roadways, railways and/or waterways for the transportation of freight (Steadieseifi, Dellaert, Nuijten, Van Woensel, & Raoufi, 2014). The problem involves two main actors, namely the *network planner* and the *network users*. The *network planner* can represent national, regional or international government authorities, responsible for determining whether or not to improve/establish physical links to the network (such as rail and road segments) or implement policy regulations with the use of governments limited budgets. *Network users* are the users of network segments, and refers to land and shipping companies that provide cargo transport with the use of trucks, trains or ships. 'Freight' and 'cargo' will be used interchangeably in this research, and refer to any type of goods/commodities transported by the *network users*. Likewise, investment alternatives are considered to be a policy decision and are use interchangeably in this research. Cargo flow distributions on the network depend on the *network users* route choice behavior, thus the *network planner* needs to understand their route choice behavior to predict the responses of formulated policies on the cargo flow distributions over the multimodal network. Consequently, the *network planner* is motivated to minimize the total costs for the *network users*, while making decisions on the the network design (Wang & Meng, 2017).

Tax regulations, green policies and alternative options to move freight at lower costs have promoted the use of multimodal transportation during the last decades (Fotuhi & Huynh, 2018), highlighting the need to encompass all dimensions of sustainable transport goals set by the government into transport models (Macharis Bontekoning, 2004). The estimation of freight flows over a multimodal network is rather complex, as *network users* are faced with several alternative routes to transport their cargo, which differ in many attributes, such as the modes of transportation, costs of transport and transfer, transport and transfer times, among others. The planning of multimodal transport infrastructure is thus a challenging task. Multimodal Network Design Problems (MNDP) deal with the establishment and improvement of links on an existing network, with a given transport demand. The main goal is to make an optimal investment decision to minimize the total travel cost in the network, while accounting for route choice behavior of *network users*. The main problems related to the MNDP are the the long computation times in real world applications (Zhang, Wiegmans, & Tavasszy, 2013) and the complexity of the solution algorithm, as it involves bi-level optimization, that is a NP-hard mixed integer algorithm (Farahani, Miandoabchi, Szeto, & Rashidi, 2013; Gao, Wu, & Sun, 2005). Heuristic approaches offer an alternative to the complexity of such algorithms and its long computational times, generating reasonable results with lower computational times (Wang & Meng, 2017).

The challenge is thus to strategically plan for multimodal transport networks subject to a maximum expendable budget, while predicting *network users* behavior and encompassing governments' sustainable transport goals. This research presents an approach that is able to quantify the impacts of transport infrastructure investments, referred to as *A Decision Support Tool*. The proposed approach makes use of heuristic solutions to overcome the long running time and complexity of MNDP algorithms. To incorporate *network users* preferences and sustainable transport goals of governments into the model, a choice behavior model is used, in which attributes including the social, economic and environmental dimensions of transportation are included. The proposed approach consists of many distinguishable steps to support *network planners* (policy makers) to strategically plan for freight transport infrastructure investments, by underpinning similarities and differences in policy choices with regards to the specified government goals under a set of future transport demands.

To be precise and concise, the objective of this work is to determine non-optimal but feasible solutions for the planning of freight transport infrastructure in an existing multimodal network. A set plausible infrastructure projects is identified, network flows are calculated over the network and its impacts are quantified. To the best of our knowledge this work is the first to propose a heuristic approach for the MNDP problem in the form of a *Decision Support Tool* for strategic planning of multimodal transport infrastructure. On top of it, the proposed approach incorporates sustainable transport attributes and choice behavior attributes. To test the validity of the proposed approach the model was implemented for the case of the Brazilian freight transport network. The network has proved to be suitable for the model validity, given the country's continental dimensions and scarce railway infrastructure. The exact objective of the study is further elaborated in Sections 1.1.1 and 1.1.2.

1.1.1. Research objective

The overall objective of this study is to tackle the problem of strategically planning multimodal freight transport infrastructure. To achieve this goal three particular topics are researched. Firstly, the Discrete Network Design Problem is brought into attention, with its limitations leading to the development of a heuristic approach for the modelling of freight flows over a multimodal network. Secondly, Network Design under Route Choice Models are considered, showing the importance of considering *network users* choice behavior in the modelling of freight flows. Lastly, the literature regarding Policy Decision Making is presented, leading to the introduction of metrics related to the environmental and social aspects of transportation. Hence, the development of a *Decision Support Tool* to support *policy makers* strategically plan for multimodal transport and predict the *network users* response to the network changes.

1.1.2. Research questions

In order to fulfill the research objective, the following research question has been developed:

What Decision Support Tool can be used to assist network planners in the policy-making decisions for multimodal transport infrastructures?

Since this research question encompasses multiple aspects, it is necessary to formulate a set of sub-questions.These are intended to guide the research towards an answer to the main research question:

1. What are the main aspects to be considered by the *network planner* when strategically planning multimodal transport infrastructures?

2. What data does the *network planner* need in order to strategically plan for multimodal transport infrastructures?

3. What model can be used to quantify the effects of changes on a multimodal network?

4. How can the performance of the alternative transport infrastructure projects be evaluated by the *policy planner*?

1.2. Approach

To answer the research questions, a *Decision Support Tool* is presented, that uses a Network Flow Model to calculate freight flows and the performance of several attributes on the network as a result of changes in the transport infrastructure. The *Decision Support Tool* is presented in the form of a framework, that guides the *network planner* through the several distinguishable steps required to quantify the impacts of transport infrastructure changes on the network. The validity of the model has been tested by means of a Case Study, presented on Section 4. The model was tested with the use of publicly available origin-destination trade data, and available physical transport infrastructures. For the purpose of this study, the focus has been on the changes on the railway infrastructure, and impacts of it on a strategical level. For this reason, the infrastructure is presented in relative low detail in the model. Capacity constraints are not taken into account, and average costs of transportation and transfers are considered. Considering a higher level of detail would not only complicate the problem, but also demand more data availability.

1.3. Thesis Structure

The structure of this thesis is as follows: Section 2 presents the main research related to the problem in question, Section 3 presents and discusses on the developed methodology. In Section 4 the model validity is tested, and the data used for the model is presented. Following, Section 5 presents and discusses the obtained results. Finally, in Section6 the main conclusions drawn from this research are presented, followed by the study limitations and further research recommendations.

2

Literature Review

This chapter provides the background information necessary to understand the motivation for this research and the field in which it takes place. The related literature is classified in three main branches: network design for intermodal freight transport (Section 2.1), network design under route choice models (Section 2.2) and Policy Decision Frameworks (Section 2.3). Finally, all identified literature and main insights obtained are synthesized in Section 2.4.

2.1. Multimodal Network Design Problem for Freight Transport

Studies on multimodal transport planning have accelerated during the last decade, as demands continue to increase and freight transport plays an important role in the economy of a country (Steadieseifi et al., 2014). Discrete Network Design (DND) Problems deal with the challenge of selecting link additions or improvements on the current network, with given demand from each origin to each destination. The main goal is to make an optimal investment decision to minimize the total travel cost in the network, while accounting for route choice behavior of *network user* in response to the formulated design policies. This type of problem involves a bi-level optimization programming, divided into an upper and a lower level optimization. The upper level describes the *network planner's* decisions, and its goal is to find an optimal project to re-designing the network with a given budget constraint defined by the government. The lower level represents the *network user* behavioral problem, who seeks to minimize total costs of transportation. These models have been continuously studied during the last decades, probably because they are highly complicated, practically important and multidisciplinary. Such a solution algorithm poses one of the most difficult and challenging problems in transport, as it is a non-linear bi-level mixed integer programming. The problem becomes particularly complex when it involves real-world large size networks (Farahani et al., 2013; Gao et al., 2005).

Santos, Limbourg, and Carreira (2015) proposed an innovative mixed integer intermodal freight location-allocation model, based on hub-location theory and non-linear transport costs. The decisions to be made are related to the location of railroad intermodal terminals in the network and allocation of freight flows between the modes with the aim to minimize transport costs (which include direct operational costs, external costs and subsidies). The research discussed the impact of three freight transport policies aiming to promote railroad intermodal transport in Europe.

However, as stated by Macharis and Bontekoning (2004) there is a need of developing Operations Research techniques and heuristic approaches to develop further applications that provide smart solutions to intermodal problems for real large-scale networks. Improvement in that direction has been proposed by Arnold, Peeters, and Thomas (2004) and Yamada, Russ, Castro, and Taniguchi (2009). Arnold et al. (2004) proposed a linear heuristic approach to deal with the problem of optimally locating rail/road terminals for freight transport. The purpose of the study was to demonstrate the impact of changes in the supply of transport and changes in operating costs on the modal shares and spatial consequences on the flows. The integer linear formulation was considered as an appropriate method to solve large size problems.

2.2. Network Design Under Route Choice Models

Another stream of literature has focused on including the *network users* choice behavior into the Network Design Porblems. While this has been widely applied in urban passenger transportation models, the application of it to cargo transport is still rather limited (Wang & Meng, 2017). In this section we focus on describing choice-based optimization models available in literature.

Tavasszy, Minderhoud, Perrin, and Notteboom (2011a) innovated by proposing a model to predict the routing of container flows that includes the decision-maker perceived (dis)utility to each alternative path, based on measurable characteristics of the route (such as travel and transfer costs/time). This allows for the consideration of *network users* choice behavior, providing useful information to predict their future choices. The approach allows for simultaneous modelling of modal split and network assignment over a multimodal network. These results can be used to predict transport demands and the impact of transport policies thereon, enabling the *network planner* to strategically answer policy questions.

Yamada et al. (2009) implemented methaheuristic procedures in the upper level of the bi-level programming model for freight transportation network design. The model aimed at identifying and selecting a suitable set of actions from a number of possible actions, such as improving existing infrastructure or establishing new ones. The lower-level problem proposed, is a multimodal multi-class user-equilibrium traffic assignment problem with deterministic route utilities. A series of heuristic approaches including a genetic algorithm and tabu search based procedures were tested in realistic networks.

Meng and Wang (2011) introduced an intermodal network design problem for cargo transportation with deterministic route utilities and solved the problem using a hybrid genetic algorithm. The authors considered each route's utility (a weighted sum of transport cost and time), which measures the preference of intermodal operators towards a route.The authors considered that each terminal operator chooses the largest utility route and no intermodal operator could be better shifting to another route. All cargo flows will be routed through the lowest-cost route between each O-D pair. Loureiro and Balston (1996) looked into a bi-level multi-commodity network design problem to determine investment policies for intercity freight transportation networks by assuming that the behavior of intermodal operators in route choice follows the MNL model. A two-step heuristic algorithm based on column generation was designed to solve the model. In a recent work of Liu and Wang (2015), a global optimization algorithm was proposed to solve a continuous network design problem with the MNL describing the behavior of choice makers under Gumbel-distributed route utilities.

Wang and Meng (2017) proposed two solution methods to solve the discrete Intermodal Network Design Problem. One returned heuristic solutions while the other generates an optimal solution. The authors concluded that the heuristic procedure shows reasonable results and lower computational times, while the optimal solution shows better results at the expense of higher computational times. The researchers also include route choice into the model, in which randomly distributed utilities, defined by price and time sensitivities are considered.

2.3. Policy Decision Making

Interest in multimodal freight transport policies is growing as a result of the needs to achieve sustainable transport goals, targets and performance indicators. Sustainable transport encompasses the economic, social and environmental aspects of transportation (Macharis & Bontekoning, 2004). Performance indicators may include among others measuring modal split, CO2 emissions, transport costs, transport time, accessibility, welfare distribution, costs of investments. The challenge is thus to develop multimodal transport policies able to encompass sustainable transport goals of governments.

Tsamboulas, Vrenken, and Lekka (2007) proposed a systematic procedural framework for the development of policy action plans to promote modal shift in favour of intermodal transport. Macharis, Caris, Jourquin, and Pekin (2011) developed a framework to assess the performance of current and potential policy measures which affect the intermodal transport industry while using Operations Research modelling techniques applicable to decisions related to intermodal transport. The framework uses 3 models that act as a platform to evaluate the policies, and its focus is on the economic and environmental aspects of transport policy making.

2.4. Synthesis

The conclusion that can be drawn from the literature review is that Network Design Problems are the most suitable ones to support the policy investment decisions. However, the solution complexity of these bi-level NP-hard problems restrict its use, especially when it comes to realistic large network problems, as explained in Section 2.1. Hence, some researchers started developing heuristic approaches to cope with the complexity of the algorithms. As researched by Wang and Meng (2017), a heuristic procedure shows reasonable results and lower computational times. This illustrates the need to develop heuristics approaches to support the policy making process. Our efforts in this research focus on providing *Decision Support Tool* that overcomes the difficulties in optimization problems while coping with the complex multimodal network systems.

Next, Section 2.2 highlighted the benefits of incorporating the choice behavior of *network users* into the modelling approach. Moreover, the model developed by Tavasszy, Minderhoud, Perrin, and Notteboom (2011b) presented an approach suitable to model route and mode choice simultaneously. Lastly, Section 2.3 pinpointed the increasing need of incorporating environmental, societal and economic metrics into the modelling approach.

Therefore this research contributes to the existing literature by presenting a *Decision Support Tool* that is able to overcome the complexities of the bi-level Multimodal Network Design Problems, specially for large-size networks. Additionally, the proposed approach incorporates the choice behavior of *network users* and sustainable transport goals of *network planners*, as a response to the increasing need to provide policy measures that result in a sustainable transport. Finally, all required steps to assess the impacts of transport investments is provided. The proposed approach is able to present solid and reliable results for*network planners* and can be used on strategic level.

Based on all explanations from the Literature Review, Section 3 will focus on developing a *Decision Support Tool* for the quantification of the impacts of policy decisions on a multimodal freight transport network.

3

Methodology

This section presents the several distinguishable steps of the adopted General Model Framework, schematized on Figure 3.1. The work of Zhang et al. (2013), Zhang and Pel (2016) and Tavasszy et al. (2011a) has served as great inspiration for the definition of the adopted steps. In the framework the main building blocks required in order to answer the *network planner* questions regarding the impacts of transport infrastructure investments can be observed. The steps include the definition of the required input data for the model, which consists of the transport demand, physical network and the investment alternatives considered by the *network planner*. Following, the *Network Flow* module is used to predict the response of *network users* to the implemented *Action Plans*. The obtained results are used as an input for the *Performance Evaluation*, where the metrics obtained by the model are analyzed. All steps involved are described in the following Subsections.

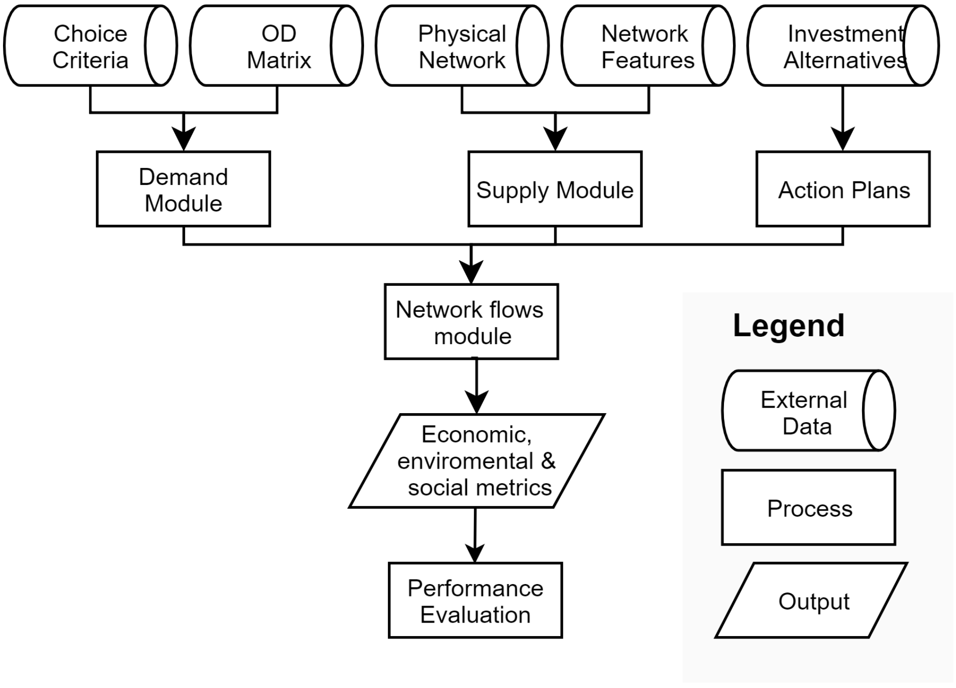


Figure 3.1: Decision Support Tool for the Strategic Planning of Multimodal Transport Infrastructure

3.1. Demand Module

The demand module consists of generating *Origin-Destination (O-D) matrices* for transport demand per commodity group on an annual basis. Demand and production regions of commodities are defined and centralized into origin and destination centroids, which are then assigned to O-D matrices to represent the aggregate flows between O-D pairs. Government databases often provide data on O-D transport demands per commodity group on an annual basis.

Following the *choice criteria* of *network users* when choosing a route for the transport of cargo is required. This choice can involve many attributes, such as geographical location of origin destination of freight, the costs involved in the transport, characteristics of the commodities. However, the intention of this study is not to study these factors, thus the attributes considered in the choice criteria are limited to cost and time of transportation/transfer. These factors have been considered sufficient to replicate the behavior of *network users* on an aggregated level (as was also pinpointed by Tavasszy et al. (2011a)). Therefore, the decision was to use a simple Logit Choice Model to represent the choices made by *network users* from a utility maximizing perspective. The average preference of *network users* towards a cheaper (μ) and towards a faster service (β) have therefore been considered. The relation of the *network users* choice behavior and the cargo flow over the network will be further elaborated on Subsection 3.2.2 and 3.4.

3.2. Supply Module

The supply side of the model is described in terms of physical infrastructure available for the transportation of the cargo, the mode types available and the corresponding travel times and distances. Since the model is designed for strategical planning of infrastructure the level of detail is constrained to geographical location of physical infrastructure, travel times and distances, as shown in Section 3.2.1. As stated by Zhang et al. (2013), for long-term planning models, the focus can be put on the infrastructure supply modelling. The network features are described in Section 3.2.2.

3.2.1. Physical Network

A multimodal freight transport network is developed with the use of a supernetwork approach, as supernetworks allow for the simultaneous choice of mode of transport and route while including transshipment points. The infrastructure of three modes of transport (rail, road and waterways) is considered in this research.

Supernetwork: the full multimodal network is referred to as the supernetwork. It consists of a directed network $G = (N, A)$, in which N is defined from N^1, N^2, N^3, N_o and N_d. The set of arcs A consists of A^1, A^2, A^3, A_o, A_d and A^t. A systematic utility value $V_{i,j}$ is associated to each arc. Following a full description of the supernetwork elements is presented. Figure 3.2 shows the components of a multimodal network.

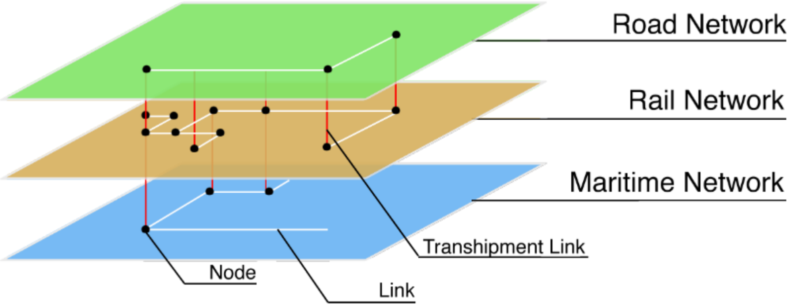


Figure 3.2: Representation of the supernetwork. Source: Clearesta (n.d.)

Modes represent the mode of transportation of the geographical link to which the node belongs to, represented by the index $m = 1,2,3$, representing the roadways, railways and waterways respectively.

Physical Network the physical networks are represented by a simple graph $G^m = (N_i^m, A_{i,j}^m)$.

Nodes and Arcs: in each graph $G^m = (N_i^m, A_{i,j}^m)$, $N_{i,j}^m$ is a set of nodes representing the physical locations i for mode m in the network. $A_{i,j}^m$ is a set of infrastructure segments belonging to one of the specified modes, referred to as *travel arcs* and representing the road, rail and water segments in the network connecting location i and j.

Origin-Destination Network a origin-destination network is used to represent the potential transport demand of a region in the coding approach.
Nodes: the model assumption is that the transport demand is shipped from origin nodes N_o to destination nodes N_d.
Arcs: N_o and N_d nodes are connected to the physical network ($G^1, G^2 and G^3$) by connectors $A_{o,j}$ and $A_{i,d}$. Origin nodes allow only outgoing flows ($A_{o,j}$) and destination nodes allow incoming flows ($A_{i,d}$). These arcs do not have any utility associated to them, as they are developed to enabled the representation of transport demand on the coding approach of the network.

Transfer Arcs directed transfer arcs A^t represent the potential mode change between nodes belonging to G^1, G^2 and G^3. As flows should be allowed in terminals in both directions, and as the model consider a directed graph, physical nodes are transformed into access and egress nodes. Transfer arcs have the access and egress nodes belonging to different graphs, and the access nodes from G^1 are connected to the egress nodes from G^2 and G^3, G^2 access nodes are connected to the egress nodes of G^1 and G^3, and lastly the G^3 access nodes are connected to the G^1 and G^2 egress nodes.

A complete representation of the nodes and arcs defined in the supernetwok is presented in Figure 3.3

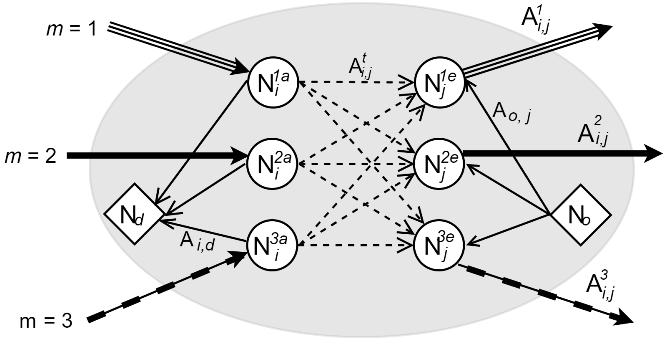


Figure 3.3: Representation of the Multimodal Network

3.2.2. Network Features

As the model is based on choice behavior, each arc is associated with the total satisfaction experienced by a user for using a particular arc, namely the arc's systematic utility. The systematic utility includes the travel time and transport costs on the arcs, as detailed in the following equations.

Travel Utility

$$V^m_{i,j} = -\beta\left(t^m_{i,j}\right) - \mu\left(c^m_{i,j} * d^m_{i,j}\right) \tag{3.1}$$

Transfer Utility:

$$V_{i,j} = -\beta\left(t^t_{i,j}\right) - \mu\left(c^t_{i,j}\right) \tag{3.2}$$

Origin-Destination Utility:

$$V_{o,j} = V_{i,d} = 0 \tag{3.3}$$

Where:

$t^m_{i,j}$: travel time between (i,j) by mode m;
$c^m_{i,j}$: transportation cost between (i,j) by by mode m;
$c^t_{i,j}$: transfer cost between (i,j)
$t^t_{i,j}$: transfer time between (i,j)
$d^m_{i,j}$: transport distance between nodes i and j by mode m
β: average preference of shippers towards a faster service (considered identical over the entire population of network users);
μ: average preference of shippers towards a cheaper service (considered identical over the entire population of network users);
$V_{i,j}$: the systematic utility of an arc.

Finally, based on the travel distance between locations and average values of CO_2 per mode of transportation, average values of CO_2 emissions in the network can be calculated. By including time, cost and CO_2 emission attributes, the utility of an arc is able to encompass social, economic and environmental aspects of sustainability into the model. Further details on how all these aspects are included in the model is presented in the Performance Evaluator Section.

3.3. Actions Plans

The following step in the framework refers to the *Action Plans*, in which two main steps take place. Firstly, an analysis of *Investment Alternatives* is required, which should encompass changes that can be measured by the proposed model.

3.3.1. Investment Alternatives

The identification of investment alternatives consists of a process in which the *network planner* identifies the problem and the alternative solutions to it. The selection of these alternatives refers to the policy choices of the government, which may involve changes to the network configuration (either expansions or improvement of road, rail or water infrastructure) and changes in regulatory policies (*i.e.* taxation of CO_2 emissions). In this research, the investment alternatives are defined manually based on a problem analysis in which relevant freight transport infrastructure plans are identified.

3.4. Network Flow Module

To model the response of *network users* to the changes of infrastructure , a network flow model inspired on the work of Tavasszy et al. (2011a) is proposed, in which the mode of transport is embedded in the network features, and choice probabilities of routes are calculated. For each of the OD-pairs (previously defined in Section 3.1), alternative paths for the transport of cargo are calculated. A path consists of a sequence of arcs connecting an origin to a destination $P_{o,d} \forall p \epsilon P$. Given the alternative paths, network flows are calculated, predicting the route choice behavior of *network users* given an Action Plan, from a utility maximization perspective. The details of the network flow model are as follows:

Route Choice: a *network user* desires to transport its cargo from origin to destination of an OD pair (V_o, V_d) and needs to make a selection of routes. The Supply Module defined in Section 3.2 and OD-matrices defined in 3.1 are the required inputs to reflect the *network user's* response to the *Action Plans*. The basis of the route choice model is a simple Logit Choice Model using path enumerations, which enables the integration of the *network user's* choice behavior to the shortest-path-algorithm. Given a fixed transport demand, it is assumed *network users* make choices based on the utility maximization. Route choices are therefore calculated from the perspective of utility maximization for the users. The total utility of a route is the sum of the utilities at each arc of the route. As the shortest path algorithm is a minimization algorithm, and the model assumption is that the *network users* make choices based on the utility maximization, the maximization problem is converted into a minimization problem. According to S. Hillier and J. Lieberman (2001), given that Z is the objective function, maximizing $-Z$ is equivalent to minimizing Z, as the smaller the Z is, the larger $-Z$ is. In other words, the solution that gives the the largest value of $-Z$ in the entire feasible region must also give the smallest value of Z in this region. Next, choice probabilities are calculated based on route specific generalized costs. The generation of the shortest path and computation of the choice probabilities is as follows:

K-shortest-path: the k-shortest-path algorithm (described in Section 3.6) has been implemented to calculate the shortest paths between origin-destination nodes in the supernetwork. The algorithm begins by calculating one *path* ($k = 1$) for each origin-destination pair (o, d), and an additional path is added to the solution, until the minimum probability constraint is violated. Once the constraint is violated, the number of paths is set as the previous calculated number of paths and the respective results are stored. This avoids a large set of variable paths and leads to an optimal number of routes.

Probabilities: based on the k-shortest-paths generated, the Logit Route Choice Probabilities are calculated for all alternatives. The probabilities of each k-shortest-path is calculate, until the probability of one of the paths violates the defined minimum probability P_{min} constraint. The Logit Route Choice Probabilities are calculated as follows:

$$P^{p}_{o,d} = \frac{e^{V^{p}_{o,d}}}{\sum_{p\epsilon P} e^{V^{p}_{o,d}}} \tag{3.4}$$

Where:

$P^{p}_{o,d}$ is the choice probability of a path p being chosen by a *network user*

$U^{p}_{o,d}$ is the route systematic utility, which is the summation of arcs systematic utilities that the route traverses through.

Flow Assignment: O-D matrices previously defined in Section 3.1 are an exogenous input for the flow assignment. Cargo flows are assigned to the paths, representing the tonnage of freight being transported on each arc of the network. The cargo flow distributed over the paths is given by the following Freight Flow equation.

$$F_{i,j} = \sum_{o\epsilon N_o} \sum_{d\epsilon N_d} \sum_{p\epsilon P} d_{o,d} * P^{p}_{o,d} * y_{i,j} \forall (i,j) \in P \tag{3.5}$$

Where:

$F_{i,j}$ is the freight flow on a specific arc of the network;

$d_{o,d}$ the demand that needs to be transported from an origin to a destination, (o,d);

$y_{i,j}$ binary variable equal to 1 if $(i,j)\epsilon P$, zero otherwise;

$P^{p}_{o,d}$ is the probability of a path p being used to serve the demand (o,d).

Outputs: the Network Flow Module provides several metrics, such as total transportation costs, total transportation times, shortest-paths between O-D pairs, modal shares, flows on arcs, CO_2 emissions. These indicators allow for the analysis of the possible impacts of the Action Plans on the network and its effects on the transport system. In short, the Route Choice models the route choice behavior of *network users*, while the Flow Assignment Model distributes cargo flows over the intermodal network.

3.5. Performance Evaluator

As the Network Flow Module deals with single-solution deterministic optimization problems, there is a need to analyze the performance of the solutions obtained to understand the impacts of each *Action Plan* proposed. For each *Action Plan* proposed the total network costs, CO_2 emissions, modal share and the respective investment costs will be used to evaluate the performance of different alternatives. Pareto Frontiers will be built to compare the performance of the solutions, where the solutions on the Pareto Frontier are the optimal ones and the other ones the sub-optimal ones. The investment costs will be used on one axis and the obtained metrics (such as total system costs) on the other axis. This provides the *network planner* with clear insights on the trade-offs of each *Action Plan* and provides results to the analysis of different compromise solutions. As suggested by Zhang and Pel (2016), the results will be analyzed from the three following perspectives:

Economic Impacts: total system costs;
Environmental Impacts: total system carbon dioxide emissions;
Social Impacts: reduction in road shares.

3.6. Solution Procedure

The proposed approach is defined as heuristic as it allows for relaxation of the hard bi-level optimization problem. A global optimal solution is not found but instead optimal local solutions are found, which lead to feasible sub-optimal solutions. This approach allows for shorter computational times. As stated by Wang and Meng (2017), depending on the size of the problem, a reasonable heuristic solution can be found within a short time to the NP-hard problem. The proposed approach is presented in **??**.

The K shortest Loopless Paths Algorithm developed by Yen (1971) is used for the Route Choice calculations (Section 3.4). The algorithm finds the K loopless paths that have the shortest lengths from one node to another in the network. It is a linear 0-1 program, which requires $O(KN^3)$ operations and $N^2 + KN$ memory addresses, where K stands for the number of shortest-paths calculated, N for the number of nodes in the network and O for the number of operations. The computational upper bound of the algorithm increases only linearly with the number of k. To enable the usage of the algorithm to the problem, capacities on the candidate routes are assumed to be unconstrained. This assumption is made as annual aggregated flow data are often used in strategic networks. Additionally, at this aggregated level, capacity shortages are rarely observed. Since congestion is mostly observed in urban areas, it is captured by the higher travel times associated to the links (Zhang, Janic, & Tavasszy, 2015). The K loopless shortest paths algorithm defined by Yen (1971) is presented in **??**.

Algorithm 1 - Network Flow Module Algorithm

```
Input: a weighted graph G=(N,A), the source nodes $o \in N_o$, the target nodes $d \in N_d$, $V_{i,j}$
Output: k-shortest-paths for all O-D combinations, total path costs, path probabilities, total generalized utilities
P = empty
k=1
for all $(i, j) \in A_{i,j}$ do:
    Assign the negative of the utility to the weights
for all $o \in N_o$, $d \in N_d$ do
    Calculate k=1 loopless shortest-path from $o$ to $d$
    Calculate the total cost of the path
    Calculate the probability of the path
    while $P_{min}$ >10% do
        store Previous Paths = k-shortest-paths, total costs of the paths, probabilities of the paths
        k = k+1
    else
        P = Previous Paths
return P
```

Algorithm 2 Finding the K loopless shortest paths in a network (Yen, 1971)

```
Input: a weighted directed graph G = (N, A), the source nodes $o \in N_o$, the target nodes $d \in N_d$,
cost of directed arc from $i$ to $j$ $V_{i,j}$, number of shortest paths to find $k$
Output: k shortest-paths $p_{o,d}$, where k = 1, 2, ... , K
for all $o \in N_o$, $d \in N_d$ do
    k = 1, $A$ = [], $B$ = []
    Determine the shortest path from $N_o$ to $N_d$ in graph G by using the Dijkstra's shortest path algorithm
for all k-1 $\forall k \in K$
    try
        for all $P_k, \forall k \in K$ do
            Get the shortest path $P_{k-1}$
            Analyze the path set of nodes $N$ by DS = {o, $n_1^{k-1}, n_2^{k-1} ... n_l^{k-1}$}
            If $P_j \in A$ and has the path as the sub path. Then set the weight of the arc from $n$ to
            its immediate neighbor to infinity for $P_j$
            Set sub path $o, n_1^{k-1}, n_2^{k-1} ... d$ in $P^{k-1}$ as the root path $R^k$ . Set the path to be determined from n to d is as the sp
            Set the path to be determined
            from n to d as the spur path, $S^k.RemovearcsinR^k fromG$
            Remove arcs in $R^k fromG$
            Compute the shortest path $P_{o,d}^k$ by using the Dijkstra's algorithm
            If path $P_{o,d}^k$ is found
            Add $R^k$, $S^k$ to form a candidate path for next shortest path. Add path to list B
            From B, move $P_{k-1}$ to A.
    except
        break
```

4

Application

To test the validity of the proposed methodology and demonstrate its use for application, the methodology is implemented for the Brazilian freight transport network. According to Meersman and Nazemzadeh (2019), the potential markets for intermodal transport are large-flow routes over long-distance. Therefore, the Brazilian freight transport network has been considered suitable to test the validity of the methodology, as Brazil is a country with continental dimensions, where long distance transport dominates. A problem overview of the Brazilian transport infrastructure and all steps required to obtain all necessary inputs for the Network Flow Module are presented in this Section.

4.1. Problem Overview in Brazil

The uneven structure of the Brazilian cargo transport matrix holds the country hostage of transport and environmental costs (Marchetti & Wanke, 2017). Brazilian transport of cargo strongly relies on the roadway network, that accounts for 65% of cargo transportation. Only 15% of the cargo is transported by railways and the other 20% is transported by waterways (*ANTF*, 2019). Several reasons are behind this situation going back many years, however these reasons are far beyond the scope of this study. The fact is that *network users* regard the low density and speed of operation of the railways as the main burdens for the use of the mode (as researched by https://www.ilos.com.br/web/panorama-das-ferrovias-brasileiras/). About 80% of the cargo transported on the Brazilian railways is iron ore (*ANTF*, 2019), a commodity tied to the rail sector and not subject to economic competition if transported by roadways. Figure 4.1 shows the modal shares of Brazil and other countries with similar dimensions, highlighting the low share of the railway as a mode of transportation. The values in green show the rail shares, followed by the road shares in red and waterway shares in blue.

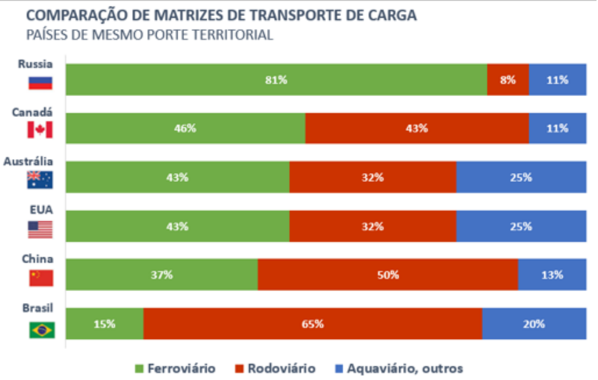


Figure 4.1: Modal Split Data ANTF

The typically long-distance transport in Brazil, combined with the low-density railway network greatly impacts the final costs of materials and goods in the country. For some time the Brazilian Transport Ministry has been planning several investments in the railway infrastructure, aiming to promote competitive and sustainable growth, promoting connectivity and bringing social benefits to the country (Brazil Government Partnerships and Investments Program, 2018).

Multimodal transportation is regarded as a key solution for governments aiming to reduce economic and environmental costs of transport caused by the high shares of road transportation. While such projects can potentially bring numerous benefits to Brazil, a sound understanding of the implications of these capital-intensive investments is of great relevance to assure long-term growth and stability to the country. Therefore, this research focuses on understanding the main impacts of railway infrastructure changes in Brazil, mainly speed changes and link additions.

When dealing with a real world case such as a study on the railway infrastructure in Brazil, it is important to use the right level of data and choose for the right precision. Considering a high level of details for the model proposed in this research is not considered of great relevance, as it deals with the problem from a strategical level of decision making. Therefore, a low level of detailing is considered suitable for the problem. Following this decision the data was consolidated in logical groups. Transport demands were aggregated into one commodity type, and average values for the required parameters are used in the model. Additionally, the generation of transport demands has been aggregated by combining neighbouring zones with the goal of achieving homogeneous transport demands over the network zones. The decision was based on the aspect that low-demand locations become irrelevant from the perspective of a strategical study, and the main advantage of railways lies with respect to cargo consolidation. Lastly, for the analysis of the model outputs, the significance of the values have been considered to the nearest million, to encompass the precision limitations of the obtained results. Therefore, the research is able to provide an aggregate description of the system and freight flows while replicating the behavior of *network users*. In the following subsections a detailed explanation of the process of data aggregation is presented.

4.2. Demand Module - OD Matrix

The data for the O/D matrix was obtained from a database made available by EPL (2018b). The O/D values were obtained based on a study of the production and attractions of zones in Brazil, which includes a total of 576 zones (19 of them being foreign countries). Data are available for the base year of 2015, and forecasts from 2020 to 2035 in 5-year intervals, under pessimistic, baseline and optimistic scenarios. Demands (given in tonnage) are divided in four commodity groups, namely: agricultural dry bulk, non-agricultural dry bulk, general cargo and liquid bulk. For this research, commodity types were aggregated into one type of cargo. Likewise, zones have been aggregated into a total of 48 zones, by combining zones with low attraction and/or production of cargo to it's neighbouring zones. Hereby we assume that zones centroids capture the weighted average location of all freight moving to, or from the zone, assuring equal relevance of each zone in terms of transport demand generated.

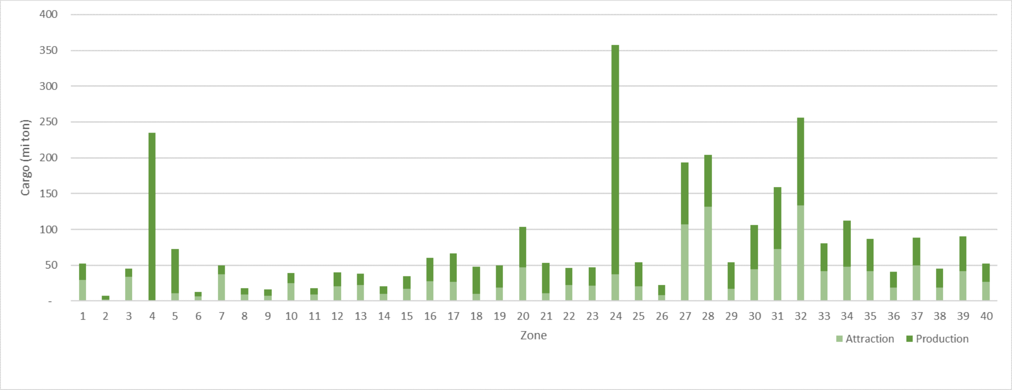


Figure 4.2: Cargo Attraction and Production on the Defined Zones

Figure 4.3 shows the defined zones on the map and figure 4.2 shows the amount of cargo attracted and produced by zones on an yearly basis. Freight attraction refers to the cargo being moved from anywhere in the world to this zone, and freight production refers to the cargo being produced in each zone and shipped to anywhere in the world. A cordon model has been defined to delimit the scope of the study. Cordon models are useful to describe the scope of a study and capture trips affecting the study area. Foreign countries located outside the defined cordon are positioned on the borders of the cordon and presented in a much lower level of detail. As mentioned by Ortúzar and Willumsen (2011), there are no hard rules for defining the location of the external cordon, it depends on the scope and decision level of the study. For this study the chosen locations for the cordon model were defined as the regions surrounding the Brazilian coast. As for this study the import-export zones had the purpose of identifying the cargo flows accessing and exiting the study area. The cordon model had to be developed in a way that ensured no flow would be transshipped on these specific zones. More details on it are specified in Section 3.2, waterway network.

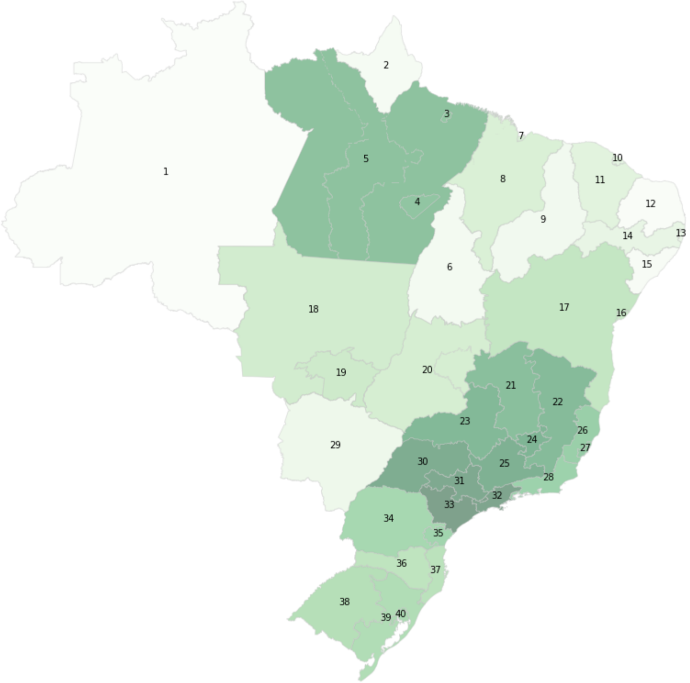


Figure 4.3: Zoning

4.3. Supply Module

On the supply side, aggregated transport networks of road, rail and waterways were used to compute travel times and distances. The model considers deterministic travel times, which is reasonable for the strategic planning horizon considered in the research. Furthermore, no capacity constraints are considered on the edges defined for the infrastructure, an assumption considered to be suitable for the strategic decision-making.The *supply module* has been defined as follows:

4.3.1. Physical Network

Roadway network: based on the zone's centroids, road travel times and distances were retrieved with the use of the Google API application. For regions predominantly composed by forests and with restricted transport infrastructure, no results could be obtained based on the zone centroids. Consequently, the centroids of these zones were moved to province capitals and/or main cities on the surroundings of the centroid (*i.e.* zones 1, 2 and 3). Based on the retrieved data a weighted average speed of 69 km/h could be observed on the roadway network, encompassing approximately 50,400 km of roadways in Brazil. The developed aggregated roadway network is shown on Figure 4.4.

Figure 4.4: Aggregated Roadway Network

Railway Network: has been aggregated based on the Railway Network provided by Brazilian railway agency *ANTF* (2019). The network aggregation can be observed in Figure 4.5, and the interested reader may refer to Appendix A for a map of the full railway network. Based on the average speeds provided by the agency, travel time between zone centroids were calculated. Based on the retrieved data the average railway speed calculated for the network is 28 km/h. With the aggregation of the network,a total length 21,000 km was considered in this project, out of the 29,075 km of railway currently present in the Brazilian territory (*ANTF*, 2019).

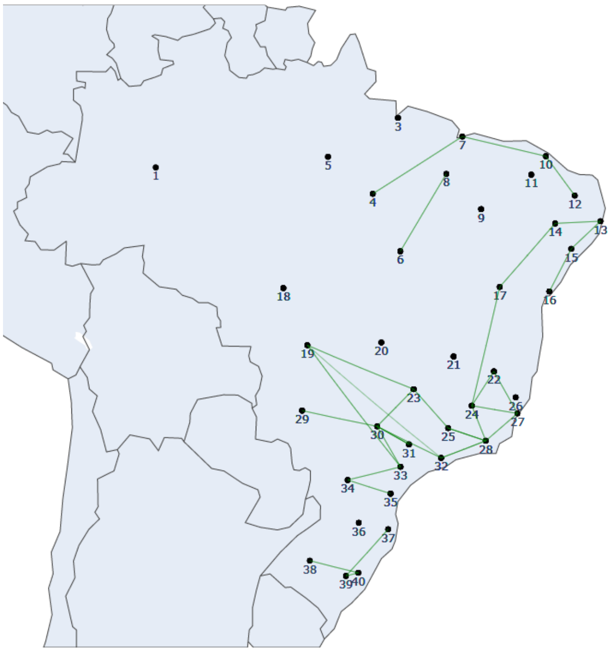


Figure 4.5: Aggregated Railway Network

With regards to the railway network, it is known that most *network users* will experience pre-end haulage to access the railway network. Zhang et al. (2013) proposed the creation of centroid-terminal connectors to connect centroids to railway terminals, representing the average pre-end haulage of shipments starting or ending in this region. Similarly, in this research the average distance of the pre/end haulage for each zone containing a railway terminal has been calculated, and the additional disutility generated by it has been included in the railway utilities. These values are of course zone specific, and directly related to the geographical characteristics of the zone (represented by the average travel distance and time for the pre/end haulage). As most shippers experience cargo transfers when using railways, transfer times and costs are always applied, with a few exceptions. As previously mentioned, about 80% of the cargo transported on the Brazilian railways refers to the transport of iron ore generated in zones 5 and 25 and exported via zones 8 and 26 & 29 respectively (information compiled from data obtained from *ANTF* (2019)). Therefore, these specific railway connections have been connected directly to the zone centroids, implying no transfer cost and pre/end haulage costs apply. This is reasonable, as for these specific cases railway terminals are located at the iron ore mines. Lastly, port zones that have direct connections by rail to other port zones follow the same rule proposed for the specific iron ore connections.

Waterway Network: was created using port nodes, and waterway links were created between them, connecting Brazilian port clusters with each other and with the export - import regions. Import-export regions are not connected between each other, but only with the Brazilian port clusters. To facilitate the modelling process, private and public ports have been clustered based on geographical location. This is reasonable as on a strategical level the transport costs to/from ports closely located are similar. The chosen clustering structure can be observed in Figure 4.6, which is based on the clustering scheme developed by the Brazilian Port Agency (BRASIL, 2015), including a total of 12 port clusters. The available port connections (waterway edges) have been based on data made available by EeSea (2019).Travel times and distances between ports has been retrieved from http://ports.com/sea-route, where a port of origin, port of destination and desired speed are given as inputs. The considered speed was 10 knots (18.52 km/h).

Figure 4.6: Cordon Model - Port Nodes

The cordon model location was defined in a way that assures no cargo is transferred at any of the import-export zones. To do so the main consideration was regarding the distances from Brazilian port clusters to the import-export zones. The cordon model has been set in a way that transport distance and time between Brazilian port clusters is always inferior than to an import-export zone. In this way only the cargo produced or attracted by the foreign zones will be transported through these water connections. In Table 4.1 the Brazilian port clusters and the zone number associated to them is presented. It is assumed that the ports are directly connected to the zone centroids, as port zones are mostly large metropolitan areas that generate high transport demands. The interested reader can refer to Appendix A for details on the ports encompassed by Brazilian port cluster.

Table 4.1: Port Zones

Zone	**Port Cluster**	**Zone**	**Import - Export Zones**	
		41	Peru	Argentina
1	Cluster Amazonas - Santarém		Colômbia	Paraguai
7	Cluster Maranhão-Vila do Conde		Suriname	Uruguai
10	Cluster Ceará		Guiana Francesa	Chile
12	Cluster Rio Grande do Norte		Guiana	Bolívia
13	Cluster Pernambuco		Venezuela	Equador
16	Cluster Bahia	42	America Central	
27	Cluster Espírito Santo	43	America do Norte	
28	Cluster Rio de Janeiro	44	Europa	
32	Cluster São Paulo	45	África	
35	Cluster Paraná-São Francisco do Sul	46	Ásia	
37	Cluster Itajai-Imbituba	47	Ásia-África-Paises Árabes	
40	Cluster Rio Grande do Sul	48	Oceania-Austrália	

4.3.2. Network Features

Table 4.2 shows the average values of time and cost of transport and transfer adopted for the model. Transport cost estimates for the year of 2019 were provided by a cost expert from EPL (2018b). The values were provided by commodity group, and the average of these values has been adopted as this study has aggregated commodities into one group. Average levels are considered for all attributes and assumed to be the same over the whole network. Given the difficulties involved in obtaining average values when modelling transport flows on an entire country, several sources were used to obtained the required values for the model.

Table 4.2: Mode attributes

Mode	Road	Rail	Water	Source
Freight rate ($R\$/ton-km$)	0.8479	0.4365	0.2654	EPL (2018a)
CO_2 emissions ($kg-CO_2/ton.km$)	0.75	0.033	0.033	average values calculated based on (UK (2019)

As services vary greatly per rail terminal and port, as well as per commodity type, adopting average values of transfer costs and times is a challenging task. Nevertheless, reasonable values were obtained from distinct sources and are shown in Table 4.3.

Table 4.3: Transfer attributes

Modes		Transfer Cost (R$/ton)	Transfer Time (h)
Road	Rail	16.03	24
Road	Water	19.68	75
Rail	Water	22.5	24

Sources: values obtained and adapted from Rumo (n.d.), EPL (2018b),Clearesta (n.d.)

Lastly, time (β) and cost (μ) sensitivity values were obtained from a state-choice experiment conducted by Empresa de Planejamento e Logistica (n.d.) with 13,039 companies. The experiment was conducted with shippers from all over the country, and global values for the sensitivity values were calculated, as shown in Table 4.4.

Table 4.4: Choice Behavior Coefficients

Choice Behavior Coefficients	
β	-0.0156
μ	-0.0169
Source: EPL (2014)	

4.4. Action Plans

The development of the Action Plans has been made based on the Railway Infrastructure projects proposed by the Brazilian National Railway Association (*ANTF*, 2019). Subsection 4.4.1 describes the railway infrastructure plans and based on it *Action Plans* are developed and presented in Subsection 4.4.2.

4.4.1. Investment Alternatives

Based on the plans from the *ANTF* (2019), possible investment alternatives have been defined. The Brazilian National Railway Association has developed and proposed a set of railway projects (as shown in Appendix A). The projects proposed have been linked to the zone centroids defined in this research, and the average distance by railway between the zone centroids is considered to be equal to the road distance between the same centroids, as the distance information is not available for several projects. Investment costs have been computed based on an average cost of construction of 7 million R$/km (information retrieved from http://www.antt.gov.br/). Transfer costs and average road access and egress have been considered by using the same approach proposed for the currently available railway network. The considered project alternatives are depicted with black lines on Figure 4.7, and the details of each project can be observed in Table 4.5.

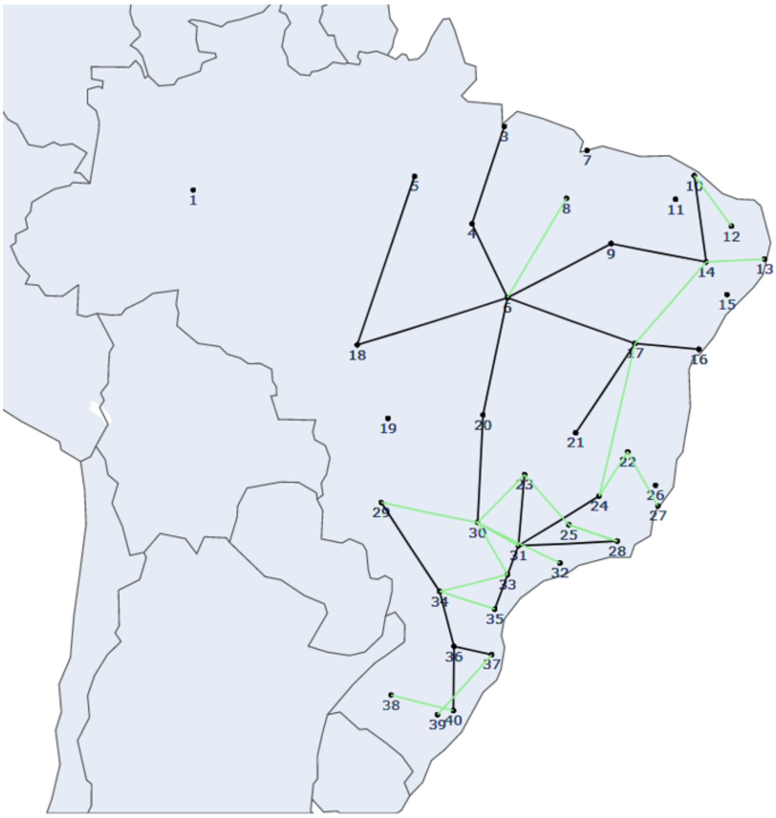


Figure 4.7: Government Railway Construction Plans

Table 4.5: Brazilian Government Railway Infrastructure Plans

Line	Origin	Destination	Construction Costs (bi R$)
Ferrovia de Integracao Oeste Leste	17	16	3.05
Ferrovia Ferrogrão	5	18	14.45
Ferrovia Norte Sul	6	20	5.38
Ferrovia Norte Sul	20	30	4.95
Ferrovia Centro Atlântica	21	17	6.27
Transnordestina	10	14	5.04
Transnordestina	14	9	5.52
Conexão Transnordestina / Norte-Sul	9	6	7.66
Prolongamento Norte-Sul	6	4	4.94
Prolongamento Norte-Sul	4	3	5.04
Ferrovia de Integracão Oeste Leste	6	17	6.96
Ferrovia de Integracão Centro Leste	6	18	9.19
Campinas	24	31	5.38
Triângulo Mineiro	23	31	3.28
Corredor Ferroviário do Paraná	29	34	5.50
São Paulo - Curitiba	31	35	3.99
Ferrovia Norte Sul	34	36	3.09
Ferrovia Norte Sul	36	40	3.10
Corredor Ferroviário de Santa Catarina	36	37	2.27
Campinas - Rio de Janeiro	31	28	5.01

4.4.2. Proposed Action Plans

To test the effects of the proposed Railway Projects on the network, several action plans have been defined, as specified in Table 4.6 and depicted on Figure 4.8. As previously mentioned, the average speed on the Brazilian railway tracks is considered to be 28 km/h, and impacts of establishing new railway connections that offer the same speed has been calculated. Additionally, the impacts of establishing railway connections with higher speeds were also computed. Lastly, the investment costs have been defined.As already stated, the average cost of construction of railways is 7 million R$/km for standard railways. Additionally, investments in projects considering railways that operate under what ANTT considers as medium speed are estimated to be 25 mi R$/km (average speed of 150km/h).

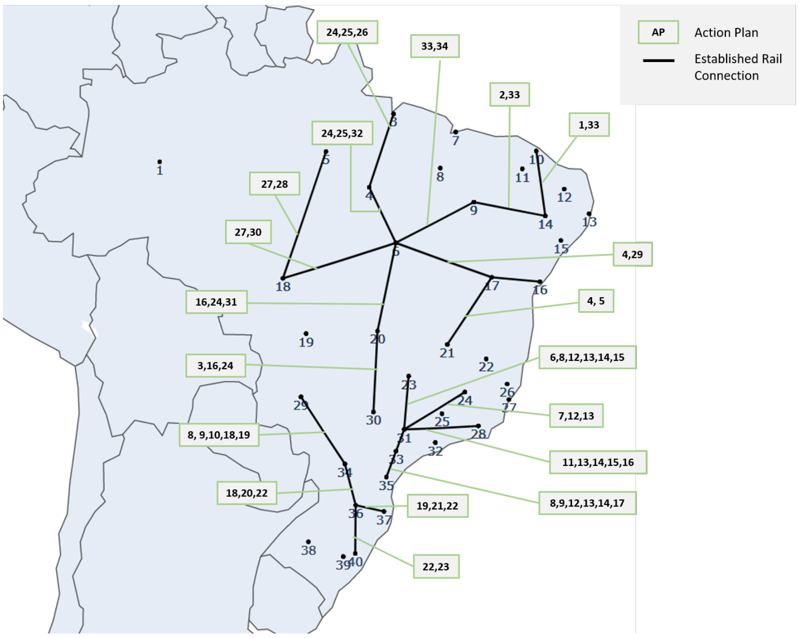


Figure 4.8: Proposed Action Plans depicted on the Brazilian map

Table 4.6: Proposed Action Plans

Action Plan	**Established Connections**								**Investment (mi R$)**	
	Connection A		Connection B		Connection C		Connection D		28 km/h	150 km/h
1	10	14							5,040	7,380
2	14	9							5,521	8,085
3	20	30							4,949	7,247
4	21	17	6	17					13,226	19,367
5	21	17							6,961	10,193
6	23	31							3,275	4,796
7	24	31							5,383	7,882
8	29	34	35	31	31	23			12,768	18,695
9	29	34	35	31					9,492	13,899
10	29	34							5,502	8,057
11	31	28							5,005	7,329
12	31	35	23	31	31	24			12,648	18,521
13	31	35	23	31	31	28	31	24	17,653	25,849
14	31	35	23	31	31	28			12,648	18,521
15	31	35	23	31					7,265	10,638
16	31	35	30	20	20	6			14,322	20,972
17	31	35							3,990	5,843
18	34	29	36	34					8,594	12,584
19	34	29	36	37	36	34			10,864	15,908
20	34	36							3,091	4,527
21	36	37							2,271	3,325
22	36	40	36	37	36	34			8,457	12,384
23	36	40							3,095	4,532
24	4	3	6	4	6	20	20	30	20,307	29,735
25	4	3	6	4					9,975	14,606
26	4	3							5,040	7,380
27	5	18	6	18					23,643	34,620
28	5	18							14,448	21,156
29	6	17							6,961	10,193
30	6	18							9,195	13,464
31	6	20							5,383	7,882
32	6	4							4,935	7,226
33	9	6	9	14	14	10			18,216	26,674
34	9	6							7,655	11,209

5

Case study : results and interpretation

The evaluation of the Case Study Results take place in this Section. The *Network Flow Module* results are presented and discussed, as well as the process of defining the most suitable Action plans for analysis, and their impacts on the model. Transport demand for 2020 under a baseline scenario were considered both for the *Reference Case* and for the proposed *Action Plans*. Before starting the process of analyzing the impacts of infrastructure investments, a face validity session took place, and the results and discussions of this session are presented in Subsection 5.1. Following the impacts of the proposed Action Plans and their results are discussed in terms of economic, environmental and social aspects, as proposed in Section 3.5. For the economic impacts (presented in Section 5.2) the main metric analyzed was total transportation costs. Furthermore, the options were analyzed in terms of the environmental footprint, by the metric of CO_2 emissions caused by the network in Section 5.2.3. Lastly, the results where analysed in terms of modal shift from road to rail, and distribution of flows throughout the country, to encompass the social impacts of the Action Plans (Section 5.2.4). The probability threshold for the Network Flow Module has been set to 10% and parameters have been considered to be deterministic.

5.1. Face Validation

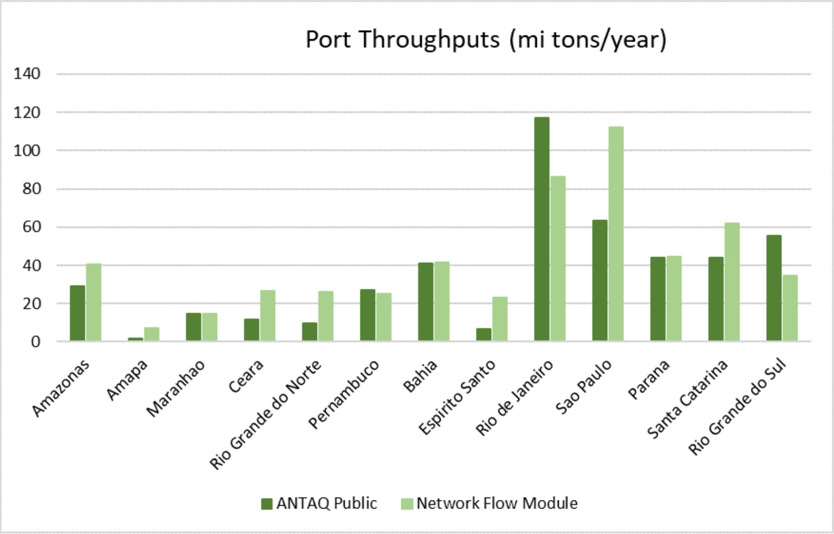


Figure 5.1: Comparison of Model Port Throughputs and ANTAQ database

To ensure the validity of the results of the model a face validation session took place, and two consultants from the Port of Rotterdam were presented with the Network Flow Module Results. Given the fact that the expertise of the consultants is mainly on port flows, the validation focused on checking the port throughput values. For the validation, the transport demand of 2015 under the baseline transport demand forecast was chosen, to enable the comparison with the port throughput data that was made available by ANTAQ (2019). The network flows were computed considering the current multimodal transport infrastructure available, as it was presented in Section 4. Table 5.1 shows the difference in the computed port throughputs between the data made available by ANTAQ (2019) and the Network Flow Model developed in this research, which are also illustrated in Figure 5.1.

Table 5.1: Validation of Modelled Port Throughputs

Port Cluster	Annual Port Throughputs (mi tons)		Difference in Throughput (mi tons)
	ANTAQ Public	Network Flow Module Results	
Amazonas	29	41	12
Amapa	2	7	5
Maranhao	15	14	-1
Ceara	12	27	15
Rio Grande do Norte	10	26	16
Pernambuco	27	25	-2
Bahia	41	42	1
Espirito Santo	7	23	16
Rio de Janeiro	117	86	-31
Sao Paulo	63	112	49
Parana	44	44	0
Santa Catarina	44	62	18
Rio Grande do Sul	55	34	-21
Pará	57	0	-57
Mato Grosso do Sul	4	0	-4
TOTAL	525	544	19

According to the experts, the model has been able to properly compute the network flows for the ports, as the computed port throughputs are not only in line with the values they expected, but also comparable to the observed values obtained from ANTAQ (2019). One of the main identified limitations of the model was the inability of the model to account for capacity constraints and commodity types. Therefore, flow shifts have been observed in port clusters that are closely located geographically. A clear example of this are the examples of the Espirito Santo, Rio de Janeiro and Sao Paulo port clusters. ANTAQ predicts higher cargo flows in Rio de Janeiro and lower in Sao Paulo when compared with the modelled flows. The same situation can be observed with Santa Catarina and Rio Grande do Sul. By modelling the cargo flows for all commodity types, it is not possible to restrict which type of cargo can be handled by each port. On the other hand, the experts believe that the results show a potential market share increase at the port of Sao Paulo. This could be researched in more detail to analyze and understand the potential of the port. Nevertheless, the obtained results have proven to be consistent with the current situation of Brazilian cargo flows and were in line with expectations of the experts. More details regarding the face validation procedure can be found in Appendix B.

Following a comparison of the modal shares has been made. According to *ANTF* (2019), the current modal split in Brazil is: 15% rail, 65% road and 20% water (as presented in Figure 4.1). If only road and rail are considered, one can arrive at the values of 81% share of road and 19% of rail. The proposed model has been able to calculate the model shares rather accurately, as the calculated values show a modal split of 81.49% for road and 18.51% for rail. Also the model indicates that if all proposed projects presented in 3.3.1 are implemented a modal split of 32.9% for the rail can be expected, against 67.1% for the roadways. That is still not comparable to the other countries with similar dimensions presented in Figure 4.1. China has a share of 42.52% for railways when only compared with road transportation, and the USA and Australia have a 49.42% share of the rail mode when compared to the road (values obtained based on the results from Figure 4.1). This is a consequence of the current condition of Brazilian railways, as explained in Section 4.1. The modal shares computed by the Network Flow model for the Reference Case, as well as the values presented by the Reference Case and ANTF are presented in Figure 5.2.

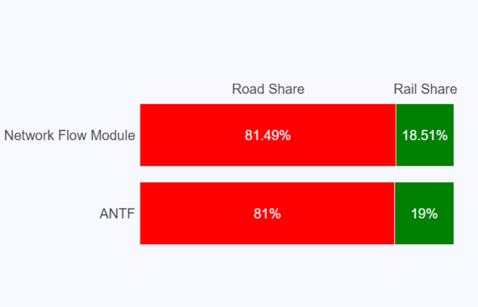


Figure 5.2: Data Validation Modal Split

5.2. Analysis of Action Plan Results

In this Section we start by analyzing the model results for the elaborated Action Plans (subsection 5.2.1). The first step consisted of analysing the economic results in terms of total costs on the network, followed by an analysis of the effects of the Action plans on individual segments of the network (Subsection 5.2.2). Next the results were analyzed in terms of environmental and social impacts.

5.2.1. Economic Analysis of Action Plans

As presented in Table 4.6 the Action Plans have considered speeds of 28km/h and 150km/h, as ANTT has stated the average values of investments for rail infrastructure to be 7 mi R$/km for standard railways and 25 mi R$ for medium speed railways (average speed considered to be 150 km/h). For the initial analysis it was assumed that the average speed on the new rail segments will be comparable to the current speeds on the current network. A Pareto Frontier has been drawn for the proposed Action Plans, where the total cost savings are compared to the investment costs of each Action Plan. Figure 5.3 shows the results obtained, where the first number on the marker annotation refers to the Action Plan number and the second one refers to the considered speed of the Action Plan. The frontier shows the optimal solutions, where the total network costs and investment costs are both minimized. The solutions out of the pareto frontier are thus considered as sub-optimal ones. Therefore, the conclusion is that with the given investment costs, the speed of 150 km/h does not lead to optimal results. This means that the additional savings in costs do not lead to optimal solutions when the investment costs for the rail infrastructure are of 25 mi R$/km. The Pareto Frontier shows that significant reduction in cost savings are observed for investment of around 5bi R$, where Action Plans 7, 26, 3 and 32 show remarkable cost savings. A policy recommendation that can be drawn from this results is that if the *network planner* is planning on investing approximately 5 bi R$, the best option from an economical perspective is to invest in Action Plan 7, followed by 26, 3 and 32 respectively. Another insight provided by the frontier refers to the decision of investing 10 bi R$. Even though Action Plan 25 is on the frontier, a combination of two actions that cost 5 bi R$ would lead to higher cost savings. The recommendation would thus be investing on Action Plans 7 & 26 (where total network cost savings sum up to 1760 mi R$/year). It is important to note that when deciding for the combination of Action Plans, further analysis must be made to guarantee the proposed Action Plans do not influence the cargo flows of one another. For the combination of Action Plans 7 & 26 the changes are not expected to be substantial, as the two proposed investments are on regions located in completely different geographical regions.
A last remark regarding the Pareto Frontier is that it's results must be critically assessed. One example refers to AP 20, that did not generate any cost savings on the network but is considered as one of the "optimal solutions" presented on the frontier. That is simply because the investment of the Action plan is low and no other Action plan has been proposed with the same/similar investment. Therefore, no option has been made available with the same investment cost and additional cost savings.

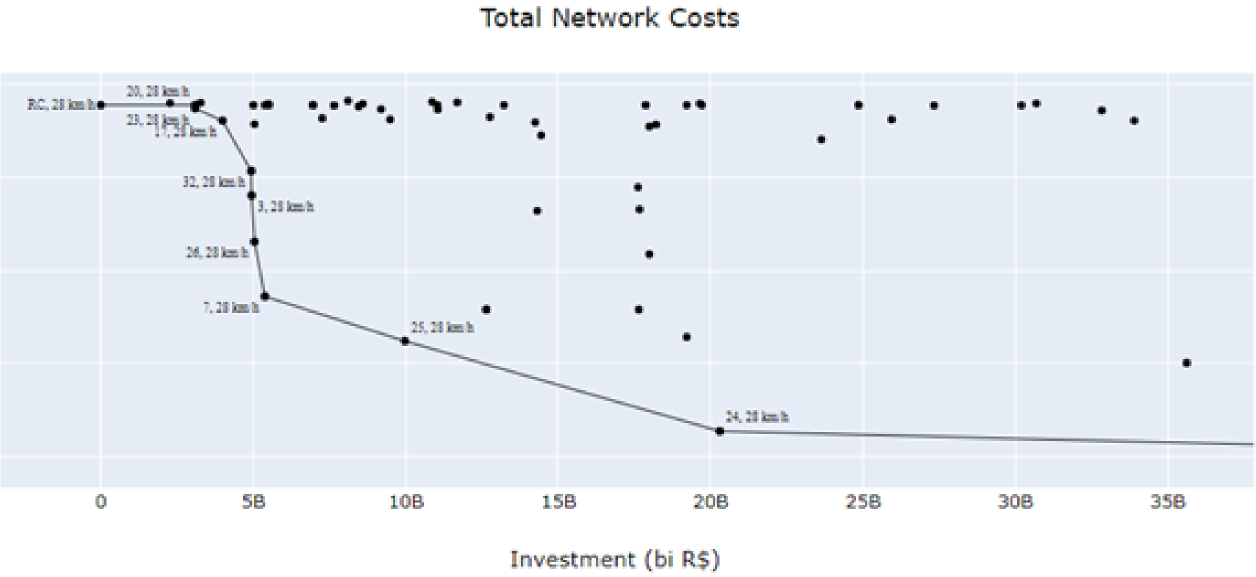


Figure 5.3: Pareto Frontier - Total Transport Costs for speeds of 150km/h and 28 km/h

The results shown on the Pareto Frontier, aligned with the fact that the real operating speed of the new railway segments is unknown, has led to the decision of analyzing the performance of the proposed Action Plans under the consideration of speeds of 50km/h and 100km/h. Benefit Cost Ratios were calculated for each of the Action Plans by dividing the gains on the network in terms of total transportation costs (mi R$/year) and time savings (mi R$/year), by the investment costs (thousands R$). In order to monetize the time savings, the value of time of *network users* was obtained by dividing β/μ, which resulted in a value of time of 0.92 R$/ton-km. Investment costs for the speed of 50 km/h and 100 km/h have been considered to be 7 mi R$/km, as the goal is to understand if the increase in speed on the railways does lead to better results. Additionally, it is reasonable to assume speeds higher than 28 km/h for newly established railways, as the speeds on the railway network in Brazil are mostly low as a result of aging infrastructure and insufficient maintenance for the past decades. Figure 5.4 shows that with the given investment costs considered for railway connections of 150 km/h, the benefits of investing in standard railway infrastructure are higher. Additionally, it can be observed that under the hypothesis that the investment in railways able to operate on the speeds of 50km/h and 100 km/h is the same as the standard railways, the higher speeds generate higher BCR. That is because when the railways operate in higher speeds, they attract higher amounts of cargo as network users have a higher preference towards a fater service. Therefore, the conclusion drawn is that railways operating at higher speeds generate higher savings to the network, however, an analysis has to be made regarding the additional investment costs incurred from higher railway speeds.

Additionally, the results lead to the conclusion that Action Plans 2, 4, 5, 6, 10, 11, 18, 19, 20, 29, 31 and 34 are not generating any cost savings to the network. In case of AP's 11, 18, 19 and 20 the short travel distances between the zones does not provide significant benefits for network users. The rail mode requires the transfer of the cargo, which implies transfer costs and time, as well as pre-end haulage, that become significant for the total transportation costs in the case of short distance connections. For Action Plans 2, 4, 5, 6, 10, 29, 31 and 34 there is an additional burden to the attraction of cargo on the newly established connections caused by the model assumption of average pre-end-haulage times and distances to the zone centroids. As the zones in the model were defined by production and attraction of cargo, their geographical area varies substantially. The zones where the railway connections were established in the previously mentioned Action Plans present significant geographical dimensions, resulting in high average access-egress times for the rail terminals. It is important to keep in mind that the travel times and costs on the alternative paths on the network (namely the alternatives by road and water) also influence the attraction of cargo on the railways. Therefore, the results highlight the challenge of investing on short distance railways, as *network users* become more sensitive to the pre-end haulage and transfer costs/times. Following, the challenges of investing in railways in regions with lower cargo flows is pinpointed by the burden caused by the high pre-end haulage costs.

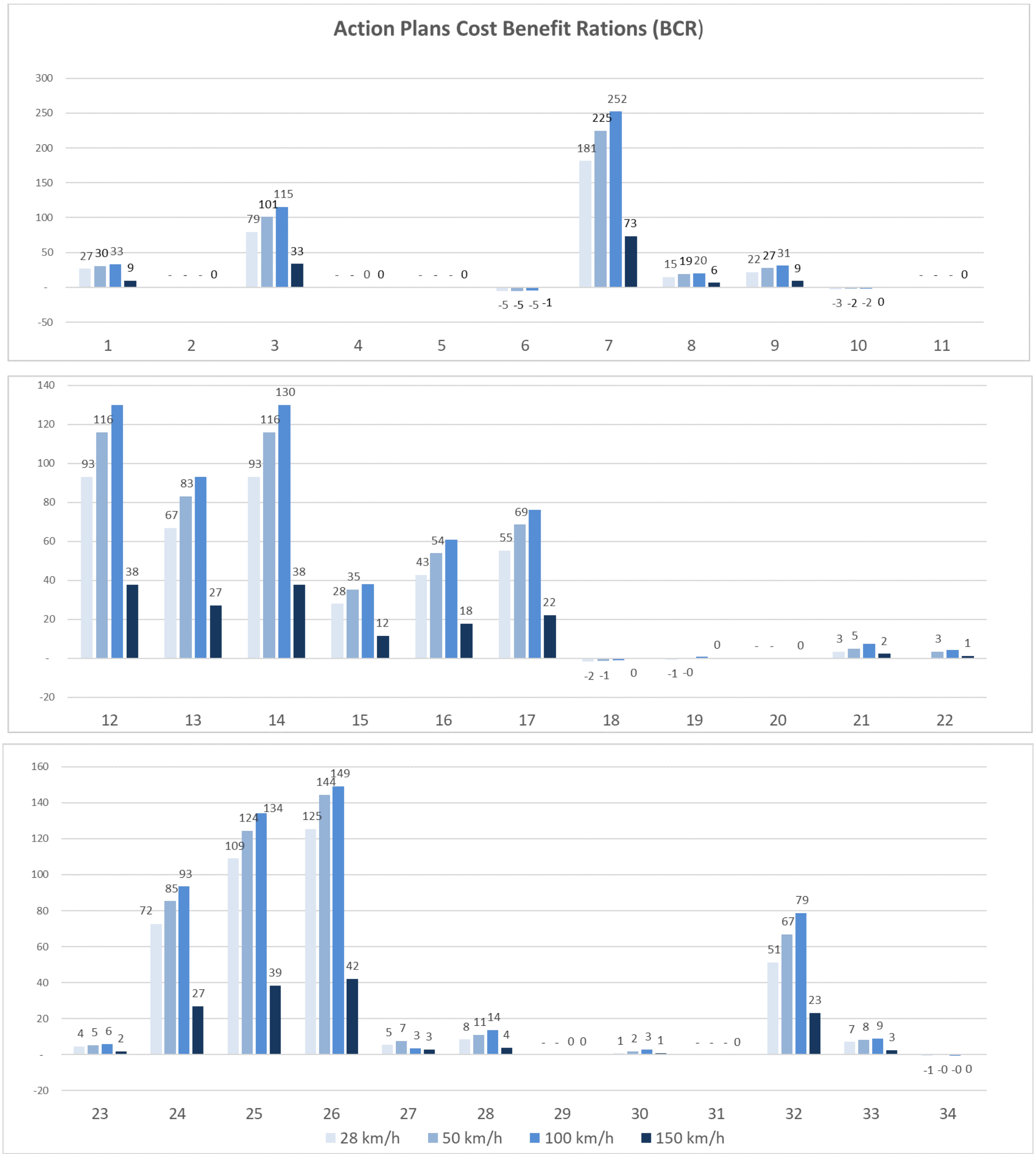
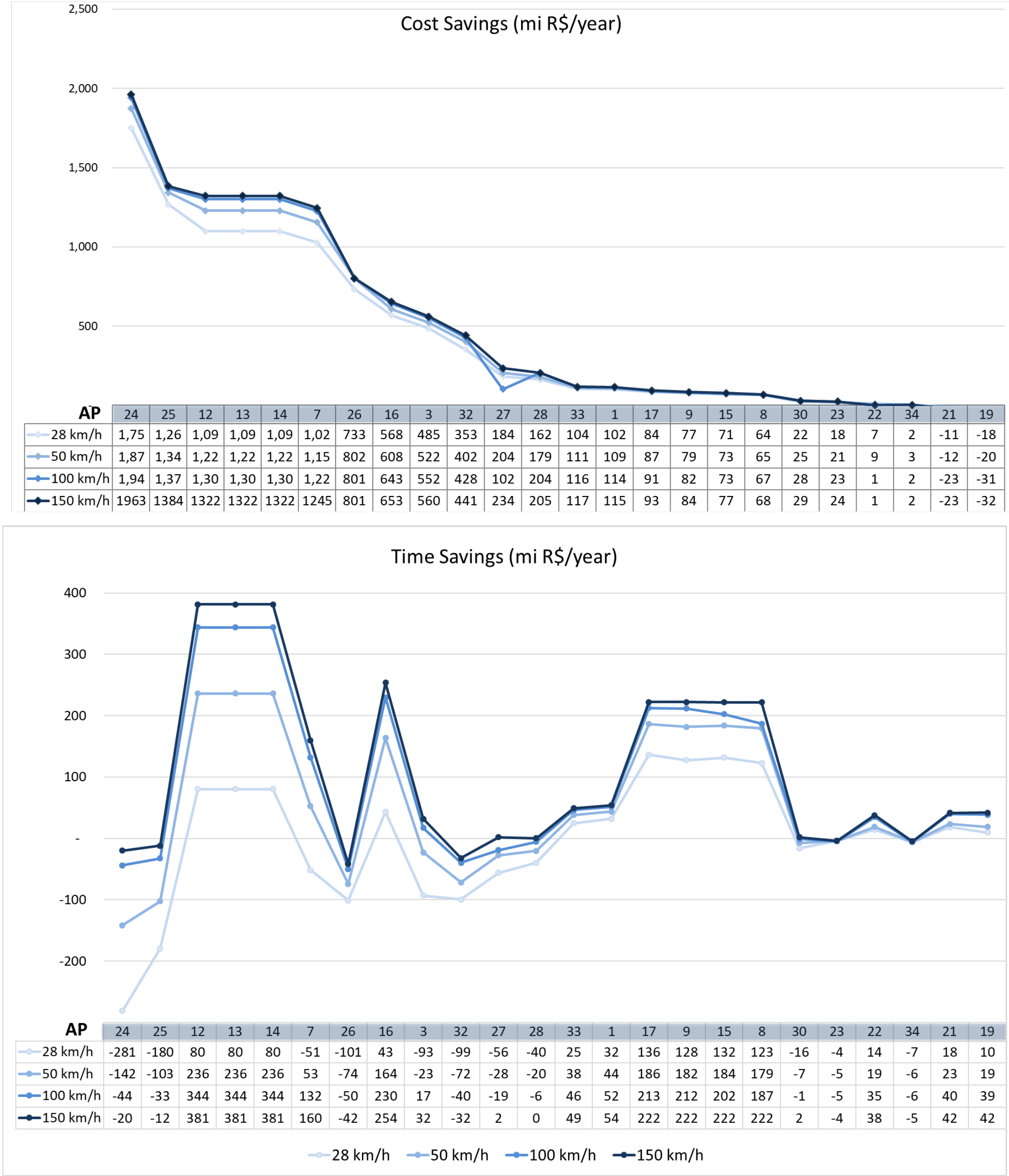


Figure 5.4: Benefit Cost Ratio of Action Plans under the consideration of different railway speeds

Lastly, Figure 5.5 shows how time and cost savings might differ for each action plan. The results have been plotted on a descending order of cost savings, and the actions plans that did not result in any cost and time savings have been removed from the analysis. The graph makes the trade-off between transport costs and times clear. While Action Plan 24 has the highest cost savings for the network, the travel times on the total network actually increase when compared to the Reference Case Scenario. That highlights the fact that *network users* are willing to switch to the railway mode to reduce the transport costs at the expense of higher transport times. The switch of cargo flows from road to rail thus generates cost savings but higher transport times due to factors such as pre-end haulage, lower operational speeds of railways and transfer times. The additional network savings generated by higher speed railways is also highlighted, as the higher the railway speeds, the higher the time savings.



AP	24	25	12	13	14	7	26	16	3	32	27	28	33	1	17	9	15	8	30	23	22	34	21	19
28 km/h	1,75	1,26	1,09	1,09	1,09	1,02	733	568	485	353	184	162	104	102	84	77	71	64	22	18	7	2	-11	-18
50 km/h	1,87	1,34	1,22	1,22	1,22	1,15	802	608	522	402	204	179	111	109	87	79	73	65	25	21	9	3	-12	-20
100 km/h	1,94	1,37	1,30	1,30	1,30	1,22	801	643	552	428	102	204	116	114	91	82	73	67	28	23	1	2	-23	-31
150 km/h	1963	1384	1322	1322	1322	1245	801	653	560	441	234	205	117	115	93	84	77	68	29	24	1	2	-23	-32

AP	24	25	12	13	14	7	26	16	3	32	27	28	33	1	17	9	15	8	30	23	22	34	21	19
28 km/h	-281	-180	80	80	80	-51	-101	43	-93	-99	-56	-40	25	32	136	128	132	123	-16	-4	14	-7	18	10
50 km/h	-142	-103	236	236	236	53	-74	164	-23	-72	-28	-20	38	44	186	182	184	179	-7	-5	19	-6	23	19
100 km/h	-44	-33	344	344	344	132	-50	230	17	-40	-19	-6	46	52	213	212	202	187	-1	-5	35	-6	40	39
150 km/h	-20	-12	381	381	381	160	-42	254	32	-32	2	0	49	54	222	222	222	222	2	-4	38	-5	42	42

Figure 5.5: Time and cost savings action plans

5.2.2. Economic Analysis on Individual Segments of the Network

Further analysis consisted of understating the changes in rail flows resulted from the establishment of new rail connections in the network. The analysis consisted of understanding which connections attract most cargo, the differences in cargo flow attraction generated by investing in single links or a combination of them and lastly the analysis of where the cargo comes from. Figure 5.6 shows the attraction of cargo flow on the newly established railway connections for each of the Action Plans. The cargo attractions for the railways under the operation speed of 28 km/h can be observed, as well as the investment cost for each connection, showing the trade-off between required investment and cargo flow attraction of rail segments. It can be observed that connections such as 31-24, 4-6, 4 - 3 and 20-30 present a great ratio between investment costs and cargo attraction. On the other hand, projects as 5 - 18, 6- 18 and 9 - 6 require large investment costs but are not able to attract substantial amounts of cargo.

The Figure shows that connections 14 - 9, 21 - 17, 31 - 21, 20 - 6 and 36 - 34 did not attract any cargo flows for any of the considered speed of operations of the railways. As previously stated, the main reasons for this are the high impact of transfer costs for short distance connections, and the high costs incurred by pre-end haulage averages for zones with big geographical areas. Additionally, the results have shown that connection 6 - 17 only attracted cargo when the railway speed was set to 100km/h and 150km/h. Likewise, connection 6 - 18 only attracted cargo flows when the railway speeds were above 100 km/h. Most of the railway connections has present similar flows under the consideration of different Action Plans. Some exceptions apply,as the case of connection 20 -30 that has lower cargo flows when AP 24 is implemented than when AP 3 or 6 are implemented. That is because a share of the cargo is attracted to connections 4-3 and 4-6 that are established on Action Plan 24. On the other hand, connection 4 - 3 shows a higher potential to attract cargo when connection 6 - 4 is established (as can be observed from the flow attractions regarding AP 24 and 26).

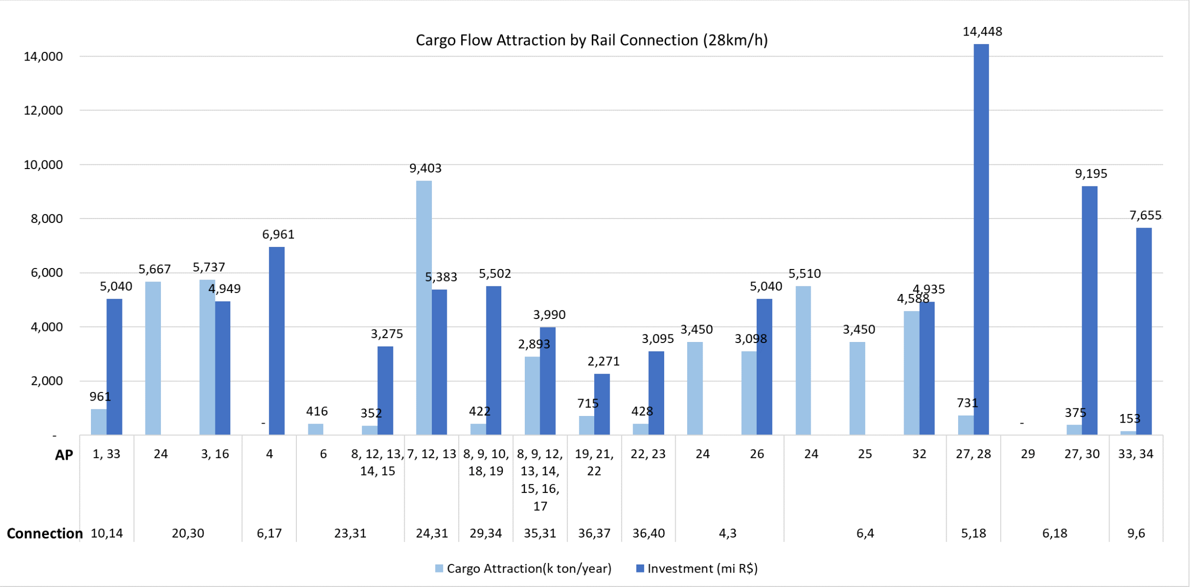


Figure 5.6: attraction of Flow on Specific Railway Segments based on the Action Plans

Additionally results have proven the hypothesis that railways attract more cargo when operating speeds are higher. Details on the obtained results can be observed on Table A.1 in the Appendix 5.1.The Table also shows the % increase expected in cargo flows in comparison with the 28 km/h operation speed. It can be observed that connections 6 - 17 and 6 - 18 were only able to attract cargo once the railway speed was set to 100km/h.

The question that raises from the analysis of the rail connections is regarding the origin and destination of the attracted cargo flows. For this analysis changes of flow have been considered significant when the amount of cargo transported was of at least 5%. Table 5.2 shows the significant changes in railway flows resulted for the developed Action Plans. Negative values represent a decrease in the flows and positive values an increase. The establishment of connection 24-31 in action Plan 7 for example leads to a reduction in cargo flows on connection 24 - 25, but an increase in flow in connection 30 - 31. Additionally, the Action Plan promoted significant changes on flows on road connections 24 - 32, 24 - 25, 31 - 25 and 17 - 21. The results have also shown that Action Plans 3 and 26 did not generate any significant changes in the flows of other rail connections, which is a remarkable result and means that the flow attracted by these connections comes from roadways. Action Plan3 has attracted cargo from road connection 30-23 and 23-20 mainly. Action Plan 26 attracted substantial amounts of cargo from connections 3-4, 4-5, 3-4 and 9-7.

5.2.3. Environmental Impacts Analysis

The improvement of the railway network leads to reduction of CO_2 emissions, as railway transport has a lower CO_2 footprint than road transport for the same distance. Therefore, in this research the Action Plans have resulted in a reduction of the environmental impact in the network. This Section presents the reduction in emissions as a result of the proposed Action Plans.

Table 5.2: Changes in Railway Flows as a Result of the Implementation of Action Plans

AP	Connection	Flow Change (%)	AP	Connection	Flow Change (%)
7	24,25	-27.11%	24	8,6	-22.05%
	25,24	-20.84%		6,8	-7.53%
	30,31	6.48%	25	8,6	-18.21%
	31,30	7.59%	32	8,6	-18.21%
10	34,29	-5.35%	33	14,10	-59.70%
12	24,25	-27.11%		10,14	-57.94%
	25,24	-20.84%		14,11	-36.27%
	30,31	6.48%		11,14	-35.41%
	31,30	7.59%		9,6	-14.07%
13	25,24	-20.84%		9,6	-14.07%
	30,31	6.48%		6,9	-13.98%
	24,25	-27.11%		6,9	-13.98%
	31,30	7.59%		14,13	-6.80%
14	24,25	-27.11%		13,14	-5.02%
	25,24	-20.84%			
	30,31	6.48%			
	31,30	7.59%			

The Pareto Frontier in Figure 5.7 shows the optimal solutions when it comes to CO_2 emissions. The results in the frontier are similar to the ones observed in the Pareto Frontier that showed the optimal solution from an economical perspective (Figure 5.3). What is remarkable is, that while Action Plan 26 performs better than options 3 and 32 in terms of total transportation costs, the situation is not the same in terms of CO_2 emissions. Thus, under the same consideration of Subsection 5.2, when the *network planner* plan to invest 5 bi R$ in the railway network, the priority order for the Action Plans is 7, 3, 32.

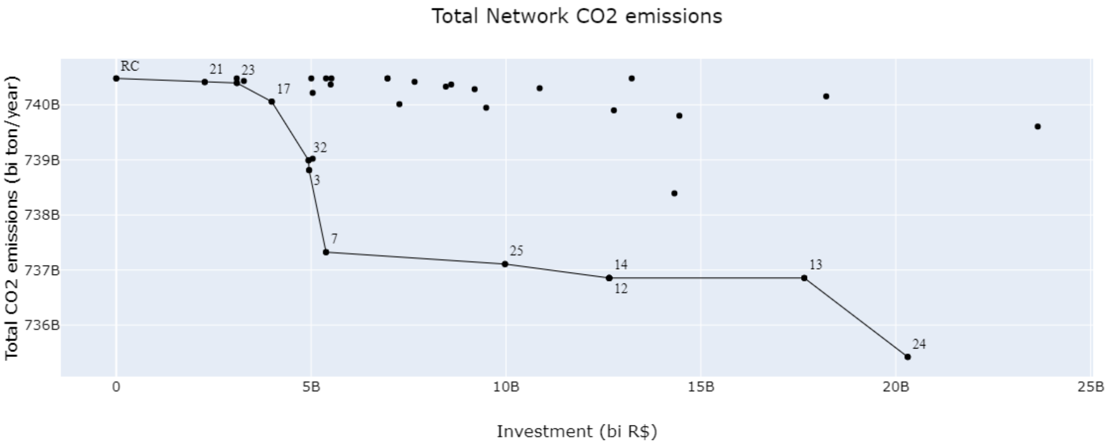


Figure 5.7: Pareto Frontier - Total CO_2 emissions - 28 km/h

Figure 5.8 shows the reduction in CO_2 emissions and the BCR for the proposed Action Plans, calculated as the reduction in CO_2 divided by the investment costs. The results confirm the conclusions drawn from the Pareto Frontier. It is interesting to see that, while Action Plans 6, 10, 18, 19, 21 an 34 did not generate any transport cost savings to the network, they did reduce the emissions of carbon-dioxide.

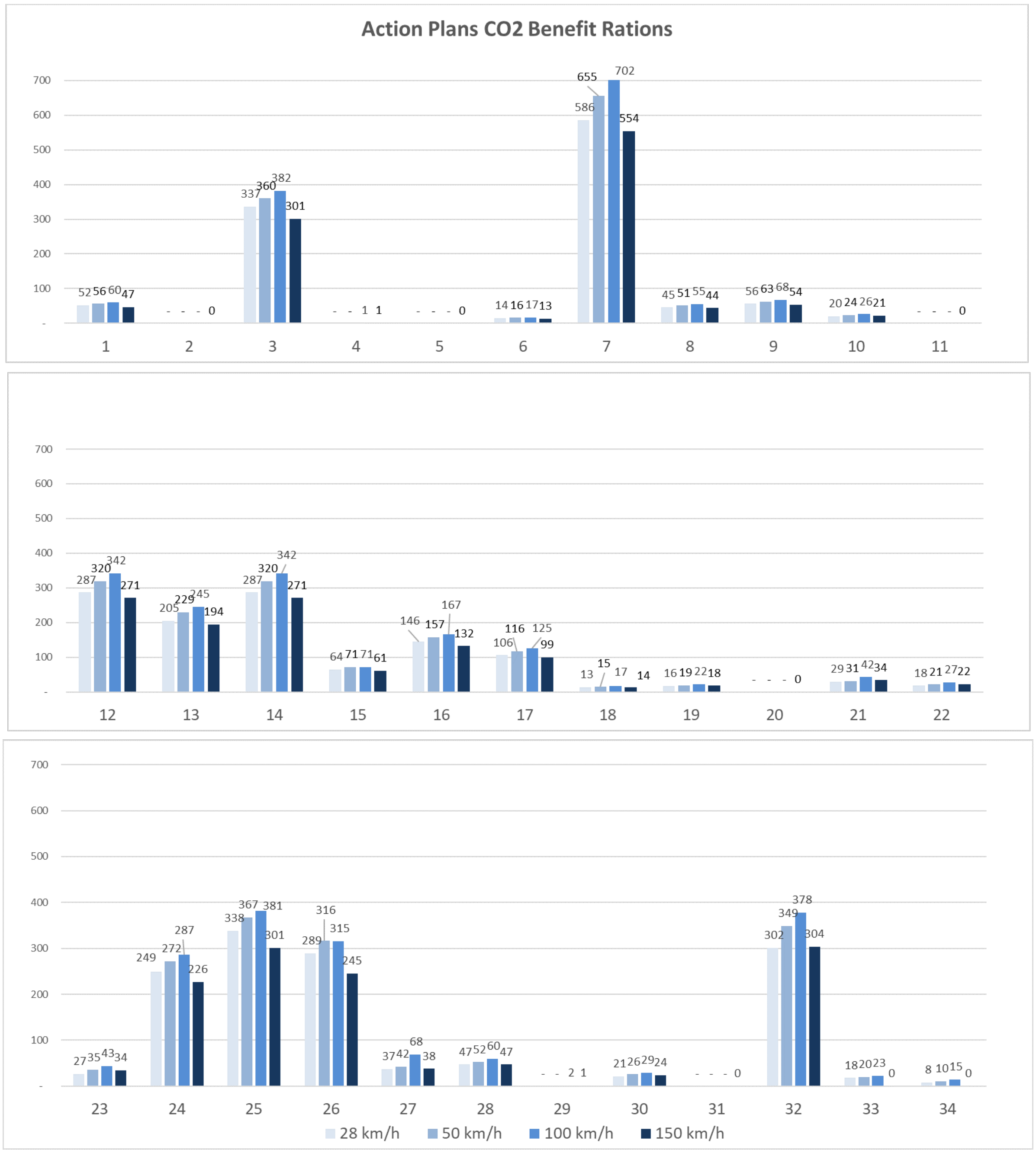


Figure 5.8: Benefit Cost rations in terms of CO_2 emissions

5.2.4. Societal Impacts Analysis

The impacts regarding the social benefits of the Action Plans have been measured in terms of modal split between rail and road. That is mainly because with the reduction of road share, congestion and accident rates are expected to decrease Macharis et al. (2011). It is important to highlight that this study did not analyze the effects of pre-end haulage of cargo on the surroundings of railway terminals on the road system.
Table 5.3 shows the share of railway transport (in % of the share) for each of the Action Plans. The additional share (%) expected for each of the action plans is shown, where the Action plans considering the establishment of rail connections with a speed of 28km/h are compared to the rail share of the Reference Case. As no significant differences in the railway shares for the different railway speeds has been observed, only the results for the speed of 28km/h are reported. The results show that there is a direct proportional relationship between investment costs and railway shares.

Table 5.3: Increase in Railway Shares as a result of the Action Plans

AP	Investment (mi R$)	Increase in Railway Shares		AP	Investment (mi R$)	Increase in Railway Shares	
		28 km/h	(%)			28 km/h	(%)
1	5,040	19.23	0.72	18	8,594	19.94	1.43
2	5,521	19.45	0.94	19	10,864	20.33	1.82
3	4,949	19.55	1.04	20	3,091	19.08	0.57
4	13,226	20.65	2.14	21	2,271	18.91	0.40
5	6,961	19.56	1.05	22	8,457	19.92	1.41
6	3,275	19.06	0.55	23	3,095	18.97	0.46
7	5,383	19.45	0.94	24	20,307	21.91	3.40
8	12,768	20.53	2.02	25	9,975	19.99	1.48
9	9,492	20.00	1.49	26	5,040	19.16	0.65
10	5,502	19.39	0.88	27	23,643	21.78	3.27
11	5,005	19.19	0.68	28	14,448	20.49	1.98
12	12,648	20.60	2.09	29	6,961	19.63	1.12
13	17,653	21.27	2.76	30	9,195	19.87	1.36
14	12,648	21.27	2.76	31	5,383	19.43	0.92
15	7,265	19.67	1.16	32	4,935	19.31	0.80
16	14,322	21.07	2.56	33	18,216	21.27	2.76
17	3,990	19.13	0.62	34	7,655	19.67	1.16

Even though one could expect the connections with the highest cost savings and reductions in CO_2 emissions to present the best improvements in terms of modal split, that has not been the case. Even though some connections are able to attract substantial amounts of cargo, this cargo can be attracted from other railways, leading to a lower increase in the rail share of the network.

5.3. The Full Economic Potential of Railway Improvements

To understand the full potential of the changes to the railway infrastructure, some extreme scenarios were built. Firstly, all proposed railway projects were considered to be built. Secondly, the operating speeds of all existing railway connections were considered to be gradually increased. Lastly, the first and second scenarios were combined, by increasing the speed on the whole network and adding all proposed railway links.

5.3.1. The Full Economic Potential of Railway Improvements

Table 5.4 shows the results obtained through these extreme scenarios. RC refers to the reference case scenario. All projects refers to a scenario where all proposed projects presented in Section 4.5 are implemented. RC networks are scenarios where the average travel speed of the railways changes to 50, 100 and 150 respectively. Lastly, in RC + All projects scenarios the network flows are calculated considering a change in the speed of all rail segments as well as the implementation of the new projects proposed. Total savings refers to the added savings resulted from cost and time savings, and the % of savings provided by each of the scenarios copared to the network costs from the Reference case. Interesting results can be seen regarding the RC Network cases, where the Total Transport Costs actually increased as a result of the speed changes. That is a result of reduced travel times of the paths that include railway segments. The reduced travel time on railway segments increases the utility of the paths, and as a result of a smaller difference in utility between the paths, a higher probability is assigned to the paths with the highest utilities. This highlights the preference of *network users* towards a faster service. It can be seen that the higher the increase in speed on the network, the more transport costs are implied, showing the willingness of *network users* to pay an additional transport cost for the travel time savings. Lastly, the results have shown that railway speed and total network savings grow in a directly proportional manner.

Table 5.4: Network Cost Savings as a result of changes over the whole network and/or implementation of all proposed projects

Established Connections	Speed (km/h)	Time Savings (mi R$/year)	Cost Savings (mi R$/year)	Total Savings (mi R$/year)	(%)
RC	28				
All Projects	50	125	3,389	3,514	0.11%
All Projects	100	378	3,547	3,925	0.12%
All Projects	150	466	3,592	4,058	0.13%
RC Network	50	23,720	-901	22,815	0.71%
RC Network	100	34,000	-1,972	32,027	1.00%
RC Network	150	37,141	-2,085	35,056	1.10%
RC + All Projects	50	23,942	2,447	27,216	0.82%
RC + All Projects	100	34,371	1,442	35,870	1.12%
RC + All Projects	150	37,595	1,499	39,415	1.22%

On Figure 5.9 the share of cost savings on the network for each of scenarios can be observed. As the speed in the railways increases, a decrease in cost savings on the rail mode is observed, and higher savings are observed on the road and waterways. That is a result of the higher flow of cargoes on the rail when speeds are increased, meaning more cargo is flowing on the railways, and less on the water and road networks. Likewise, the higher the speed of the railways, the higher the time savings on the network.

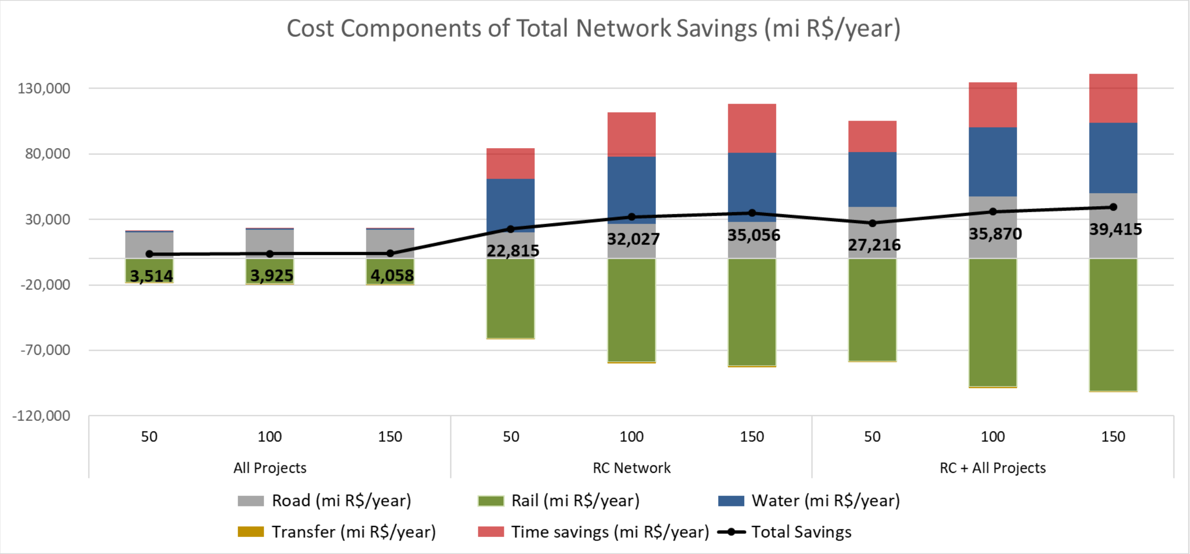


Figure 5.9: Composition of Cost Savings in mi R$/year

5.3.2. The Full Environmental Potential of Railway Improvements

In this subsection we present the full potential of railway improvements when it comes to reductions of the environmental footprint of the network. Improvements of the railway network can promote a reduction of up to 4.5% in the total CO_2 emissions of the network. Additionally, it can be observed that the higher the considered speed, the higher the reduction on the network's CO_2 emissions, as railway connections attract more cargo with higher operating speeds. It is important to bare in mind that this research did not consider a higher environmental footprint for the railway mode when the speed was increased, but instead showed the potential cargo flows that can be attracted to the rail mode and the potential reduction in the environmental footprint.

Table 5.5: Reduction in CO_2 emissions under consideration of speed changes over the whole rail network and/or implementation of all proposed projects

Established Connections	Speed (km/h)	Total CO2 emissions (mi ton/year)	Reduction in CO2 emissions (mi ton/year)	(%)
RC	28	740,480		
All Projects	28	733,272	7,208	0.97%
All Projects	50	729,356	11,124	1.52%
All Projects	100	728,504	11,976	1.64%
All Projects	150	728,305	12,175	1.67%
RC Network	50	725,916	14,564	2.00%
RC Network	100	721,345	19,135	2.64%
RC Network	150	720,258	20,222	2.80%
RC + All Projects	50	714,990	25,490	3.54%
RC + All Projects	100	709,729	30,751	4.30%
RC + All Projects	150	708,412	32,068	4.52%

5.3.3. The Full Social Potential of Railway Improvements

Lastly, Table 5.6 shows that with the implementation of all rail projects with a speed of 150km/h, railway shares are expected to increase by 20.44%. Once again, with the increase in speed of the railways, an increase in the share of the mode can be observed. Additionally the implementation of all proposed railway projects leads to an increase of up to 4.42% in the rail share.

Table 5.6: Increase in Railway Shares as a result of speed changes on the rail network and/or implementation of all proposed projects

Established Connections	Speed (km/h)	Railway Share (%)	Increase in Railway Share (%)
RC	28	18.51%	
All Projects	50	21.94%	3.43%
All Projects	100	22.76%	4.25%
All Projects	150	22.93%	4.42%
RC Network	50	33.37%	14.86%
RC Network	100	33.47%	14.96%
RC Network	150	33.49%	14.98%
RC + All Projects	50	37.50%	18.99%
RC + All Projects	100	38.70%	20.19%
RC + All Projects	150	38.95%	20.44%

5.4. Summary

To summarize, from an economical perspective the highest impacts on cost savings can be observed on Action Plans 7, 26, 3 and 32. However, results regarding the attraction of flows on the specific railway segments have shown that AP 26 and 3 attract cargo only from roadways, while AP 7 and 32 attract cargo from other railways. That is mainly because AP 6 and 26 are implemented in regions where almost no rail connections are available, whereas AP 7 and 32 are implemented on the Southeast region, where railway density is higher. The best environmental options are considered to be Action Plans 7, 3 and 32. Lastly, from a social perspective it has been observed that higher investments lead to higher shares for the rail mode. The use of choice behavior coefficients for time and cost highlighted the *network users* preferences towards times and costs. The results have shown that even though some Action Plans do not result in significant cost savings for the network (i.e. Action Plans 17, 9, 15 and 8), significant savings can be observed in terms of time savings.

Following, with the adoption of different speeds over the whole network, the full potential of the railway mode could be analyzed. Results have shown that investments in railways can lead to a reduction of CO_2 emissions of up to 4.52%, while reducing costs of *network users* of almost 40 bi R$/year (when including time savings). Lastly, the results have shown that, the higher the railway speed, the higher the benefits for the network (from all perspectives adopted by the model) and the higher the amounts of cargo attracted. This shows the preference of *network users* towards a faster railway service. However, an analysis of the investment costs is required to provide the *network planner* with a clear view of the trade offs between speed increase and investment costs.

Finally, this research has shown the importance of pre-end haulage costs for the attractiveness of railway connections. The assumption that cargo is generated on the centroid of the zones, together with the assumption of average pre-end haulage for railways has shown the importance of the location of railway terminals to attract cargo flows. For zones with low production-attraction of cargo, in which the attraction areas are geographically big the attraction of cargo to the railway is lower than when compared to smaller zones. Lastly, for the short distance rail connections the importance of transfer times and costs has been highlighted.

To finalize, this case study has proven the ability of the proposed model to support *network planners* in their decision-making for multimodal transport infrastructures. The model is able predict the mode and route choices of *network users* and their behavior as a response to network changes. Lastly, it gives great insights for the *network planner* regarding the trade-offs of the proposed investment in terms of economical, environmental and societal impacts.

6

Conclusions, Limitations and Further Research

This Section concludes the conducted research, which aimed at understating the main implications of freight transport infrastructure investments. The implications have been analyzed in terms of economical, environmental and societal impacts. Subsection 6.1 presents the main conclusions drawn from the research and Subsection 6.2 shows the opportunities for further research and development of the model.

6.1. Conclusions

In order to support *network planners* in strategically planning freight transport infrastructure investments, this research presented *network planners* with a model. This model is able to quantify the main impacts of infrastructure investments on a strategical level from an economic, environmental and societal perspective. Action Plans have been proposed and their impacts on the total network analyzed. The modelling approach does not present a detailed supply network, but it permits the construction of a realistic representation of the infrastructure network to adequately predict the main flows that will be handled by the transport infrastructure. The supernetwork approach allows the model to generate transfers between modes in an automated manner, which enables the modelling of mode and route simultaneously. Moreover, the model can easily be adapted to any other case study and/or scenario. The model validation took place with a case study for the Brazilian freight transport infrastructure, and has proven to be able to present solid and reliable results. Additionally, the results showed the applicability and value of the developed model to understand the impacts of rail infrastructure investments.

In order to answer the main research question, several steps were undertaken and sub-questions for the main research question were proposed in order to guide the researcher towards an answer for the main research question. Therefore, the answers to the sub-question are presented in this Subsection, followed by the answer to the main research question.

1. *What are the main aspects to be considered by the network planner when strategically planning multimodal transport infrastructures?* Several aspects have to be considered by *Network Planners* when strategically planning multimodal transport infrastructures. Firstly, the network planner needs to be aware of investment costs of different transport infrastructure alternatives. Following, there is a need to understand the response of *network users* to the formulated policies. Understanding the *network users'* response requires an understanding of their choices and preferences towards certain attributes (such as travel times and costs). Lastly, *network planners* must be aware of the different goals set by the government, which more and more often also include sustainable goals for transport. Therefore, when planning transport infrastructure it is of great importance to quantify the impacts of the changes in terms of social, economic and environmental impacts.

2. *What data does the network planner need in order to strategically plan for multimodal transport infrastructures?* As shown in Figure 3.1, there are four main data requirements for the planning of transport

infrastructure. Firstly, an OD-matrix is required, where transport demand between all geographical regions within the scope of the study are presented. That data can be often obtained from government databases (as it was used for the case study to validate the model of this research). Secondly, this research proposed the use of choice behavior to model the behavior of *network users* as a response to network changes. Therefore, the use of choice behavior coefficients is required, which can be obtained from stated-choice experiments. Thirdly, the model requires data regarding the available physical infrastructure, which for this research involved transport costs and times by roads, rails and water segments. Roadway data can be easily retrieved from the Google API application. Railway and Waterways data are more challenging to obtain, and can be obtained from rail and water agencies for example. Following, the model requires information regarding is referred to as Network Features. This research has used freight rates, CO_2 emissions per mode and average transfer costs and times as inputs. Lastly, the *network planner* has to decide on the investment alternatives to be considered for the model, providing data on the proposed projects and the investment costs of them.

3. *What model can be used to quantify the effects of changes on a multimodal network?* A Network Flow Model that encompasses Choice behavior of *network users* has been considered as the most suitable option to measure the effects of changes of transport infrastructure over a multimodal network. A supernetwork approach was chosen, to allow for simultaneous modelling of route and mode choice. Following, the network users' preferences were included in the modelling of freight flows by adding the systematic utility of each arc, capturing the *network users'* preferences towards costs and travel times. As systematic utilities are expressed in negative values, the MIN Z was proposed, as also suggested by S. Hillier and J. Lieberman (2001). Finally, with the use of a shortest-path algorithm with path enumerations the assignment of freight flows to several route was enable, as the route choice depends on the *network users'* preferences.

4. *How can the performance of the alternative transport infrastructure investments be evaluated by the policy planner?* The Network Flows Module returns several metrics, which can be used to analyze the performance of the different alternatives proposed by the *network planner*. The results can be measured among others in terms of total network costs savings, reduction of CO_2 emissions, modal share of the different modes of transportation and benefit, cost ratios. The performance evaluation can be made by comparing the results of the desired policies to be implemented with the results retrieved by a reference case scenario, in which the currently available transport infrastructure is considered.

What Decision Support Tool can be used to assist network planners in the policy-making decisions for multimodal transport infrastructures?

This research proposed a *Decision Support Tool for the planning of Multimodal Transport Infrastructure* that is able to predict the response of *network users* to the policy choices of *network planners*. The proposed approach is able to predict the route and mode choices over a whole network, and quantify economic, environmental and social impacts of network changes. The model has proven to present solid and reliable results, and has shown its capability of measuring the impacts of the establishment of new links on the network, which is crucial information required to support network planners in their policy-making decisions.

6.2. Limitations and Further Research

Dealing with real-world problems is not an easy task, and several challenges and limitations will be faced by one who is striving to incorporate all possible variables into a model. Additionally, the excess of information not only may distract the modeller from the main goal, but also make the analysis of the results too complex. The main challenge of this research was thus to make the right simplifications and aggregations that enabled an understanding of network freight flows on an aggregate level.

Network and parameters improvements: Due to the lack of commodity specific choice behavior coefficients, this research has used global values and aggregated commodity types as one type of cargo for the flow distribution on the network. For future research, the model can be extended to include a set of products and product specific attributes. Likewise, other appropriate and important avenues for forthcoming studies would be to include constraints on link capacities in the model. This would enable the *network planner* to measure the impacts of network changes for specific commodities and allow for more accurate results. In the same way, the model has aggregated the supply and demand networks. In the case of the demand network, zone centroids were assumed to represent the average weighted location for zone attraction and production. During the case study the implication of using zone centroids could be observed. It could therefore be interesting to consider implementing a gravity model to capture a more suitable location for zone centroids.

Multinomial Logit Model (MNL) and Choice Behavior Coefficients: As previously mentioned, incorporating commodity specific choice behavior coefficients could be beneficial to the network. Another direction for further research is developping additional coefficients (such as alternative specific constants, reliability, among others). In the same manner, the adoption of the MNL model implies that the ratio of choice probabilities of any two alternatives is independent of the presence or absence of a third alternative in the choice set. It is also noted that the MNL is unable to cope with the presence of heterogeneity among choice makers, for which the Nested Logit model or Mixed Logit model would be more suitable. The great advantage of the proposed model is that it does not assume a particular model for the choice behavior set, which gives the opportunity for further improvements in that sense.

Future Uncertainties and Scenario Analysis: The combinations of infrastructure investments has been rather restricted in this research. Not only in the sense of possible rail infrastructure investments which has been restricted to the projects proposed by *ANTF* (2019), but also since no other of infrastructure improvements were considered. The modelling of the impacts of medium speed trains (as proposed in the set of projects made available by *ANTF* (2019)), and the consideration of the establishment of links not considered in the set of proposed projects are two avenues for future research. Furthermore, the effects of policy regulations such as CO_2 taxation could be tested with the model. Lastly, one may look into the improvement of roadways, and consequently the increase of speed there. The last option would be specially beneficial in combination with capacity restrictions and travel time stochasticity. Lastly, Section 2.3 pointed out that investments to transport infrastructure are long term investments and there is a need of developing models able to cope with future uncertainties. This research assumed all variables and parameters to be deterministic, however, this assumption might be restrictive in face of uncertainties. Choice behavior coefficients, freight rates, transport times, transfer costs and times, transport demand are all fraught to uncertainties, and more robust results can be achieved when considering them as uncertain. Halim, Kwakkel, and Tavasszy (2016) proposed a scenario-discovery approach to cope with uncertainties in container transport. Research could be done to implement such an approach for the hinterland transportation, applicable for all types of cargo.

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A

Case Study Network Details

Figure A.1: Brazilian Current Operating Railway Network according to (*ANTF*, 2019)

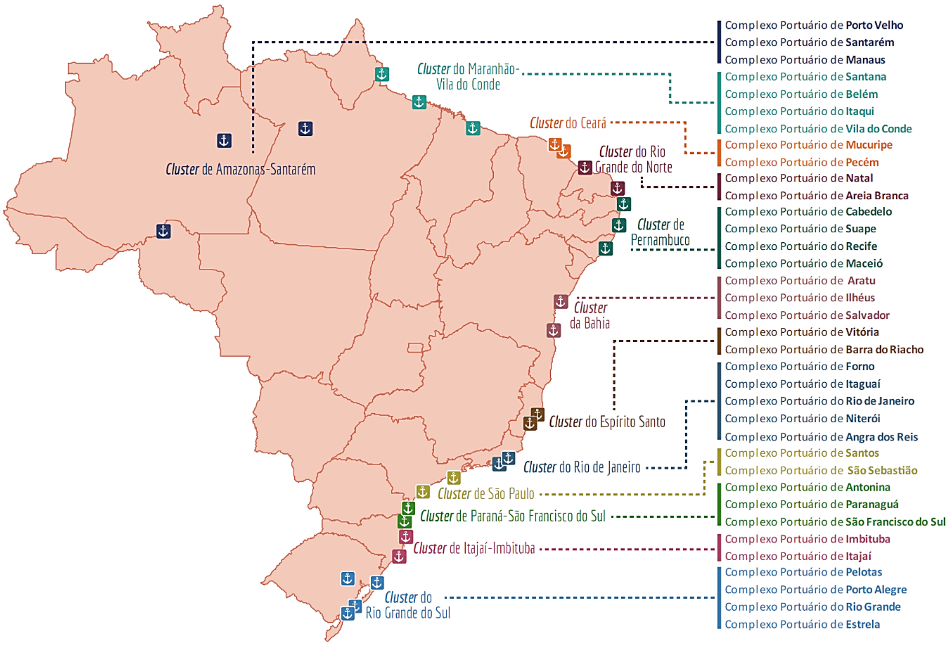


Figure A.2: Port Clusters Details (BRASIL, 2015)

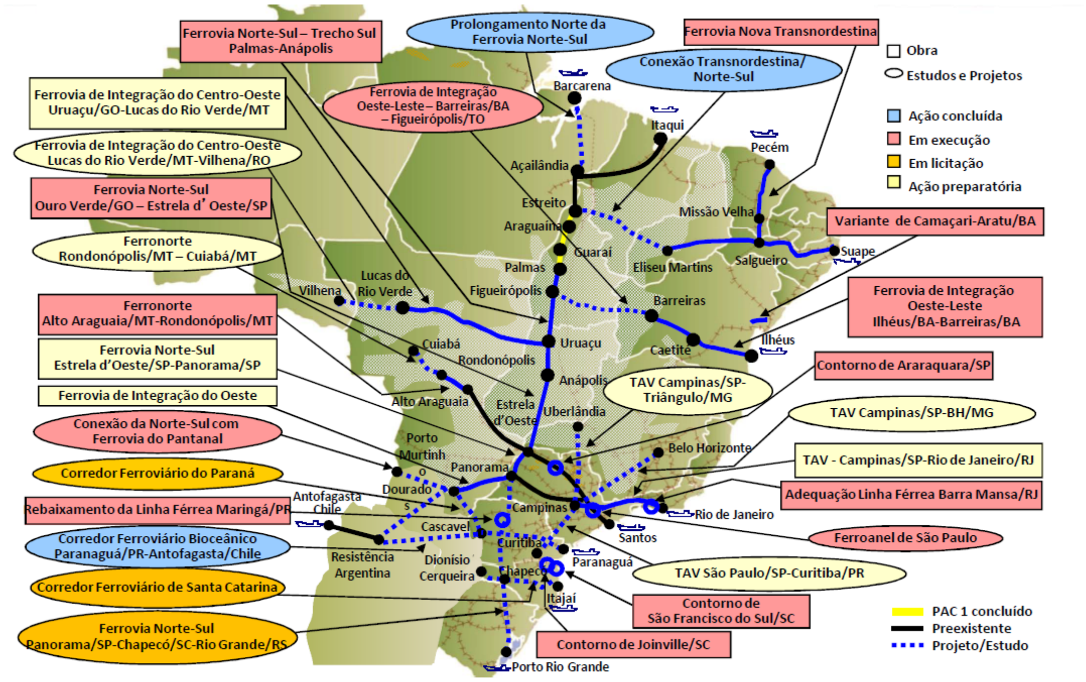


Figure A.3: Railway infrastructure Plans in Brazil (*ANTF*, 2019)

Table A.1: Flow on Railway Flows based on action plans for all considered speeds

Rail Connection	AP	28 km/h	50km/h	(%)	100km/h	(%)	150km/h	(%)
10,14	1, 33	961	1029	7.09%	1081	12.51%	1090	13.50%
220,30	24	5667	6326	11.62%	6683	17.91%	6790	19.81%
	3, 16	5737	6342	10.55%	6703	16.85%	6813	18.76%
6,17	4	0	0		30		31	
23,31	8, 12, 13, 14, 15, 6	352	391	11.25%	416	18.31%	424	20.39%
24,31	7, 12, 13	9403	10434	10.96%	11207	19.19%	11389	21.12%
29,34	8, 9, 10, 18, 19	422	497	17.75%	550	30.24%	568	34.63%
35,31	8, 9, 12, 13, 14, 15, 16, 17	2893	3235	11.80%	3445	19.06%	3517	21.54%
36,37	19, 21, 22	715	766	7.18%	1071	49.80%	1089	52.42%
36,40	22, 23	428	571	33.35%	708	65.41%	723	69.02%
24,3	24	3450	3533	2.41%	3557	3.11%	3564	3.31%
	26	3098	3405	9.90%	3415	10.23%	3418	10.32%
36,4	24	5510	6246	13.35%	6716	21.90%	6882	24.90%
	25	3450	3533	2.41%	3557	3.11%	3564	3.31%
	32	4588	5197	13.26%	5650	23.14%	5808	26.58%
5,18	27, 28	731	817	11.78%	937	28.15%	943	28.99%
26,18	29	0	0		30		31	
	27, 30	375	494	31.74%	569	51.84%	600	59.98%
9,6	33, 34	153	192	25.52%	290	89.25%	304	98.76%

B

Result Details

B.1. Face Validity Details

The experts were presented with the Figures shown in 5.1 and 5.1 which show the total imports and exports of the zones considered in the model. Whereas export values seemed to be very consistent with the ones obtained from the ANTAQ data base, the import values showed some variation, specially with regards to flows from Europe. However, according to the experts interviewed that is a common issue observed in several countries. Countries tend to keep very good track of the exported goods, but not that much attention is payed to the import flows. Moreover, Brazilian exports consist mainly of bulk, agricultural products , while a big share of the imports refers to containers, that is more difficult to control.

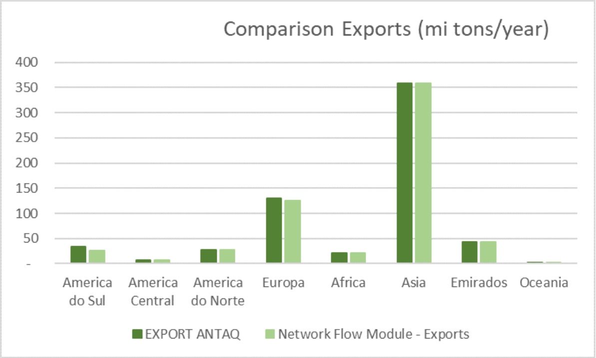
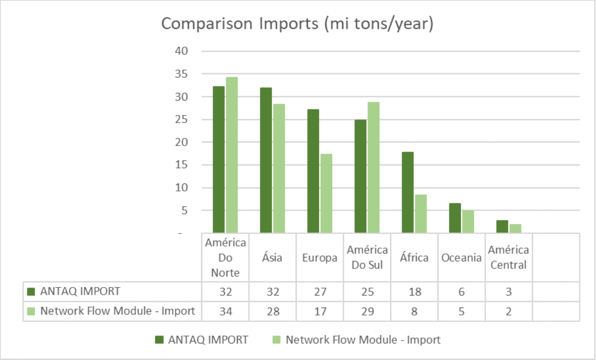


Figure B.1: Export Data Model versus ANTAQ values



	América Do Norte	Ásia	Europa	América Do Sul	África	Oceania	América Central	
🟩 ANTAQ IMPORT	32	32	27	25	18	6	3	
🟩 Network Flow Module - Import	34	28	17	29	8	5	2	

Figure B.2: Import Data Model versus ANTAQ values

Figure B.3: Import Export comparison - ANTAQ

C

Scientific Paper

A Decision Support Tool for Strategical planning of Transport Infrastructure

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ABSTRACT

The ever increasing need of developing efficient solutions for the transport of cargo, able to reduce transport costs while complying to green policies has promoted the use of multimodal transport during the last decades. Multimodal transport consists of the use of at least two modes of transportation for the transport of cargo from origin to destination [15]. Governments and transport authorities seek to make the optimal investment decisions when choosing where to allocate their budgets. To accomplish this they need to predict the response of the formulated policies on the cargo flow distributions over the multimodal network. The flow over a multimodal network is in turn dependent on the behavior of water and land transport companies (network users), aiming in minimizing their own total costs of transportation. This research has used the freight transport network of Brazil as a testing ground for the model, and focused on improvements on the railway infrastructure. The results of the model suggest that the establishment of new railway connections and increases in speed can reduce the total costs and environmental footprint of transportation over the network. Finally, according to the model assumptions, it was concluded network users have a preference towards faster railway services.

KEYWORDS

Freight transport; strategical planning; infrastructure

1 INTRODUCTION

The ever increasing need of developing efficient solutions for the transport of cargo, able to reduce transport costs while complying to green policies has promoted the use of multimodal transport during the last decades. Multimodal transport consists of the use of at least two modes of transportation, such as roadways, railways and/or waterways for the transportation of freight [15]. Therefore, governments need to choose where to investment their limited budgets over the multimodal freight transport networks and predict the responses of formulated policies on the cargo flow distributions.

The problem of planning freight transport infrastructures involves two main actors, namely the network planner and the network users. The network planner can represent national, regional or international government authorities, responsible for determining whether or not to improve/establish physical links to the network (such as rail and road segments) or implement policy regulations with the use of governments limited budgets. Network users are the users of network segments, and refers to land and shipping companies that provide cargo transport with the use of trucks, trains or ships. *Freight* and *cargo* will be used interchangeably in this research, and refer to any type of goods/commodities transported by the network users. Cargo flow distributions on the network depend on the network users route choice behavior, thus the network planner needs to understand their route choice behavior to predict the responses of formulated policies on the cargo flow distributions over the multimodal network. Consequently, the network planner is motivated to minimize the total costs for the network users, while making decisions on the the network design [18].

The Multimodal Network Design Problem (MNDP) algorithm deals with the establishment and improvement of links on an existing network, with a given transport demand. The main goal is to make an optimal investment decision to minimize the total travel cost in the network, while accounting for route choice behavior of *network users*. The main problems related to the MNDP are the the long computation times in real world applications [22] and the complexity of the solution algorithm, as it involves a NP-hard bi-level optimization [8, 9]. Heuristic approaches offer an alternative to the complexity of such algorithms and its long computational times, generating reasonable results with lower computational times [18].

This research presents an approach that is able to quantify the impacts of transport infrastructure investments, referred to as *A Decision Support Tool*. The proposed approach makes use of heuristic solutions to overcome the long running time and complexity of MNDP algorithms. To incorporate *network users* preferences and sustainable transport goals of governments into the model, a choice behavior model is used, in which attributes including the social, economic and environmental dimensions of transportation are included. The proposed approach consists of many distinguishable steps to support *network planners* (policy makers) to strategically plan for freight transport infrastructure investments, by underpinning similarities and differences in policy choices with regards to the specified government goals under a set of future transport demands. In short, this research proposes a tool that is able to support network planners in deciding on the best investment alternatives while accounting for route choice behavior of network users.

2 A BRIEF LITERATURE REVIEW ON MULTIMODAL NETWORK DESIGN PROBLEM

Studies on multimodal transport planning have accelerated during the last decade, as demands continue to increase and freight transport plays an important role in the economy of a country. Multimodal network Design Problems (MNDP) Problems deal with the challenge of selecting link additions or improvements on a multimodal network, based on a given transport demand from each origin to each destination. The main goal is to make an optimal decision investment to minimize the total travel cost in the network, while accounting for route choice behavior of *network users* in response to the formulated design policies. Literature on the MNDP problem has been presented by authors such as [15]. [14], [9], [22], [21]. This type of problem involves a bi-level optimization algorithm, divided into an upper and a lower level optimization. The upper level describes the *network planner's* decisions, and its goal is to find an optimal project to re-designing the network with a given budget constraint defined by the government. The lower level represents the *network users* behavioral problem, who seeks to minimize total costs of transportation. These models have been continuously studied during the last decades, probably because they are highly complicated, practically important and multidisciplinary. Such a solution algorithm poses one of the most difficult and challenging problems in transport, as it is a non-linear bi-level mixed integer programming. The problem becomes particularly complex when it involves real-world large size networks [8, 9].

As stated by [11] there is a need of developing Operations Research techniques and heuristic approaches to develop further applications that provide smart solutions to intermodal problems for real large-scale networks. Improvement in that direction has been proposed by [2] and [19]. [2] proposed a linear heuristic approach to deal with the problem of optimally locating rail/road terminals for freight transport, which was considered as an appropriate method to solve large size problems.

In the wake of this, this research builds upon the existing literature by presenting a *Policy Support Tool* that is able to overcome the complexities of the bi-level MNDP, specially for large-size networks. Additionally, the proposed approach incorporates the choice behavior of *network users* and sustainable transport goals of *network planners*, as a response to the increasing need to provide policy measures that result in a sustainable transport. Finally, all required tools to assess the impacts of transport investments is provided.

3 THE DECISION SUPPORT TOOL FOR STRATEGIC PLANNING OF TRANSPORT INFRASTRUCTURE

This section presents the proposed *Policy Support Tool*, that is inteded to support *network planners* in strategically planning for multimodal transport infrastructures. The intention of the model is to predict aggregate flows of freight Over a multimodal network and replicate the behavior of *network users* in order to measure the performance of several attributes on the network for different scenarios . It consists of several distinguishable steps that guide the *network planner* in the policy-decisions, as presented on Figure 1.

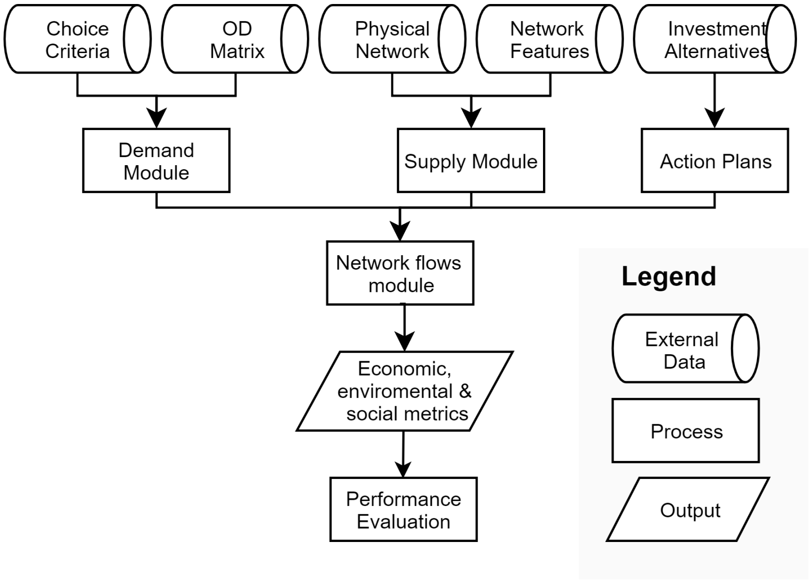


Figure 1. Decision Support Tool for the Strategic Planning of Multimodal Transport Infrastructure

3.1 *Demand Module*

The demand module consists of generating *Origin-Destination (O-D) matrices* for transport demand per commodity group on an annual basis. Demand and production regions of commodities are defined and centralized into origin and destination centroids, which are then assigned to O-D matrices to represent the aggregate flows between O-D pairs. Government databases often provide data on O-D transport demands per commodity group on an annual basis. Next, the *choice criteria* of is defined to replicate the behavior of *network users* on the network. As the aim of the model is to replicate this behavior on an aggregate level, the attributes considered in the choice criteria are limited to cost and time of transportation and transfer [16]. A simple Logit Choice Model has been used to represent the choices made by *network users* from a utility maximizing perspective. The average preference of *network users* towards a cheaper (μ) and faster service (β) have been considered. The relation of the *network users* choice behavior and the cargo flow over the network will be further elaborated on Subsection 3.2 and 3.4.

3.2 *Supply Module*

The supply side of the model is described in terms of physical infrastructure available for the transportation of the cargo, the mode types available and the corresponding travel times and distances (network features). A supernetwork approach has been used to allow for the simultaneous choice of mode of transport and route while including transshipment points. The supernetwork consists of a directed network $G = (N, A)$, in which N is defined from N^1, N^2, N^3, N_o and N_d. The set of arcs A consists of A^1, A^2, A^3, A_o, A_d and A^t. A systematic utility value $V_{i,j}$ is associated to each arc. Following the details of the supernetwork are described, and illustrated in Figure 2.

Modes represent the mode of transportation of the geographical link to which the node belongs to, represented by the index $m = 1, 2, 3$, representing the roadways, railways and waterways respectively.

Physical Network the physical networks are represented by a simple graph $G^m = (N_i^m, A_{i,j}^m)$. In each graph $G^m = (N_i^m, A_{i,j}^m)$, $N_{i,j}^m$ is a set of nodes representing the physical locations i for mode m in the network. $A_{i,j}^m$ is a set of infrastructure segments belonging to one of the specified modes, referred to as *travel arcs* and representing the road, rail and water segments in the network connecting location i and j.

Origin-Destination Network a origin-destination network is used to represent the potential transport demand of a region in the coding approach.

Nodes: the model assumption is that the transport demand is shipped from origin nodes N_o to destination nodes N_d. *Arcs:* N_o and N_d nodes are connected to the physical network $(G^1, G^2 and G^3)$ by connectors $A_{o,j}$ and $A_{i,d}$. Origin nodes allow only outgoing flows $(A_{o,j})$ and destination nodes allow incoming flows $(A_{i,d})$. These arcs do not have any utility associated to them, as they are developed to enabled the representation of transport demand on the coding approach of the network.

Transfer Arcs directed transfer arcs A^t represent the potential mode change between nodes belonging to G^1, G^2 and G^3. As flows should be allowed in terminals in both directions, and as the model consider a directed graph, physical nodes are transformed into access and egress nodes. Transfer arcs have the access and egress nodes belonging to different graphs, and the access nodes from G^1 are connected to the egress nodes from G^2 and G^3, G^2 access nodes are connected to the egress nodes of G^1 and G^3, and lastly the G^3 access nodes are connected to the G^1 and G^2 egress nodes.

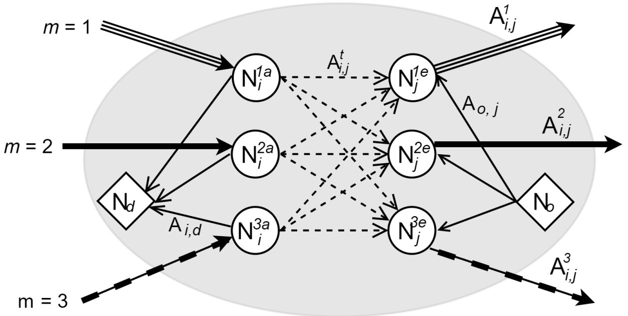


Figure 2. Representation of the Multimodal Network

As the model is based on choice behavior, each arc is associated with the total satisfaction experienced by a user for using a particular arc, namely the arc's systematic utility. The systematic utility includes the travel time and transport costs on the arcs, as detailed in the following equations.

Travel Utility

$$V^m_{i,j} = -\beta\left(t^m_{i,j}\right) - \mu\left(c^m_{i,j} * d^m_{i,j}\right) \qquad \textbf{Equation 1.}$$

Transfer Utility:

$$V_{i,j} = -\beta\left(t^t_{i,j}\right) - \mu\left(c^t_{i,j}\right) \qquad \textbf{Equation 2.}$$

Origin-Destination Utility:

$$V_{o,j} = V_{i,d} = 0 \qquad \textbf{Equation 3.}$$

Where:

$t^m_{i,j}$: travel time between (i, j) by mode m;

$c^m_{i,j}$: transportation cost between (i, j) by by mode m;

$c^t_{i,j}$: transfer cost between (i, j) ;

$t^t_{i,j}$: transfer time between (i, j) ;

$d^m_{i,j}$: transport distance between nodes i and j by mode m

β: average preference of shippers towards a faster service (considered identical over the entire population of network users);

μ: average preference of shippers towards a cheaper service (considered identical over the entire population of network users);

$V_{i,j}$: the systematic utility of an arc.

Finally, based on the travel distance between locations and average values of CO_2 per mode of transportation, average values of CO_2 emissions in the network can be calculated.

3.3 *Action Plans Module*

The identification of investment alternatives consists of a process in which the *network planner* identifies the problem and the alternative solutions to it. The selection of these alternatives refers to the policy choices of the government, which may involve changes to the network configuration (either expansions or improvement of road, rail or water infrastructure) and changes in regulatory policies (*i.e.* taxation of CO_2 emissions). In this research, the investment alternatives are defined manually based on a problem analysis in which relevant freight transport infrastructure plans are identified.

3.4 *Network Flows Module*

A network flow model inspired on the work of [16] has been developed to calculate the network flows of each of the proposed *Action Plans*. The model calculates the shortest paths between all origin-destination pairs in the network from a utility maximization perspective and assigning the flow to them. A path consists of a sequence of arcs connecting an origin to a destination *P (o,d)* where $p \epsilon P$. The model details are as follows.

Route Choice a *network user* desires to transport its cargo from origin to destination of an OD pair (V_o, V_d) and needs to make a selection of routes. The Supply Module defined in Section 3.2 and OD-matrices defined in 3.1 are the required inputs to reflect the *network user's* response to the *Action Plans*. The basis of the route choice model is a simple Logit Choice Model using path enumerations, which enables the integration of the *network user's* choice behavior to the shortest-path-algorithm. Given a fixed transport demand, it is assumed *network users* make choices from a utility maximization perspective. The total utility of a route is the sum of the utilities on each arc of the route. As the shortest path algorithm is a minimization algorithm, and the model assumption is that the *network users* make choices based on the utility maximization, the maximization problem is converted into a minimization problem. According to [?], given that Z is the objective function, maximizing $-Z$ is equivalent to minimizing Z, as the smaller the Z is, the larger $-Z$ is. In other words, the solution that gives the the largest value of $-Z$ in the entire feasible region must also give the smallest value of Z in this region. Next, choice probabilities are calculated based route specific generalized costs. *K-shortest-path:* the k-shortest-path algorithm proposed by [20] has been implemented to calculate the shortest paths between origin-destination nodes in the supernetwork. The algorithm begins by calculating one *path* $(k = 1)$ for each origin-destination pair (o, d), and an additional path is added to the solution, until the minimum probability constraint is violated. Once the constraint is violated, the number of paths is set as the previous calculated number of paths and the respective results are stored. This avoids a large set of variable paths and leads to an optimal number of routes. *Probabilities:* based on the k-shortest-paths generated, the Logit Route Choice Probabilities are calculated for all alternatives. The probabilities of each k-shortest-path is calculate, until the probability of one of the paths violates the defined minimum probability P_{min} constraint. The Logit Route Choice Probabilities are calculated as follows:

$$P^p_{o,d} = \frac{e^{V^p_{o,d}}}{\sum_{p \epsilon P} e^{V^p_{o,d}}} \quad \textbf{Equation 4.}$$

Where:
$P^p_{o,d}$ is the choice probability of a path p being chosen by a *network user*
$V^p_{o,d}$ is the route systematic utility, which is the summation of arcs systematic utilities that the route traverses through.

Flow Assignment O-D matrices previously defined in Section 3.1 are an exogenous input for the flow assignment. Cargo flows are assigned to the paths, representing the tonnage of a commodity being transported on each arc of the network. The cargo flow distributed over the paths is given by the following Freight Flow equation.

$$F_{i,j} = \sum_{o \epsilon N_o} \sum_{d \epsilon N_d} \sum_{p \epsilon P} d_{o,d} * P^p_{o,d} * y_{i,j} \forall (i,j) \in P \qquad \textbf{Equation 5.}$$

Where:

$F_{i,j}$ is the freight flow on a specific arc of the network;

$d_{o,d}$ the demand that needs to be transported from an origin to a destination, (o, d);

$y_{i,j}$ binary variable equal to 1 if $(i, j) \epsilon P$, zero otherwise;

$P^p_{o,d}$ is the probability of a path p being used to serve the demand (o, d).

The final outputs of the model are total transportation costs, total transportation times, shortest-paths between O-D pairs, modal shares, flows on arcs, CO_2 emissions. These indicators allow for the analysis of the possible impacts of the Action Plans on the network and its effects on the transport system.

3.5 *Performance Evaluation*

As the Network Flow Module deals with single-solution deterministic optimization problems, there is a need to analyze the performance of the solutions obtained to understand the impacts of each *Action Plan* proposed. For each *Action Plan* proposed the results obtained in the Network Flows Module and their respective investment costs will be used to evaluate the performance of different alternatives. Pareto Frontiers will be built to compare the performance of the solutions, where the solutions on the Pareto Frontier are the optimal ones and the other ones the sub-optimal ones. The investment costs will be used on one axis and the obtained metrics (such as total system costs) on the other axis. This provides the *network planner* with clear insights on the trade-offs of each *Action Plan* and provides results to the analysis of different compromise solutions. As suggested by [21], the results will be analyzed from the three following perspectives: *Economic Impacts*: total system costs; *Environmental Impacts*: total system carbon dioxide emissions; *Social Impacts*: reduction in road shares;

3.6 *Solution procedure*

The proposed approach is defined as heuristic as it allows for relaxation of the hard bi-level optimization problem. A global optimal solution is not found but instead optimal local solutions are found. A pseudo-code of the developed algorithm is presented bellow.

4 **APPLICATION**

To test the validity of the proposed methodology and demonstrate its use for application, the methodology is implemented for the Brazilian freight transport network. Brazilian transport of cargo strongly relies on the roadway network, that accounts for 65% of cargo transportation. Only 15% of the cargo is transported by railways and the other 20% is transported by waterways [1]. Several reasons are behind this situation going back many years, however these reasons are far beyond the scope of this study. The fact is that *network users* regard the low density and speed of operation of the railways as the main burdens for the use of the mode (as researched by https://www.ilos.com.br/web/panorama-das-ferrovias-brasileiras/). About 80% of the cargo transported on the Brazilian railways is iron ore [1], a commodity tied to the rail sector and not subject to economic competition if transported by roadways. The uneven structure of the Brazilian cargo transport matrix holds the country hostage of transport and environmental costs [12]. This research aims in understanding the impacts of railway infrastructure investments in Brazil, with the aim of providing *network planners* with a sound understanding of the implications of railway investments to the transport network.

Algorithm 1 Network Flow Module Algorithm

```
Input: a weighted graph G=(V,E), the origin nodes $V_o'$, the destination nodes $V_d$, $V_{i,j}$
Output: k-shortest-paths for all $V_{o,d}$ and assigned flows on each defined arc, total network costs, total network $CO_2$ emissions, modal
P = empty
k=1
for all $V_{i,j} \epsilon G$ do:
    Assign the negative of the utility to the arcs
for all $V_{o,d} \epsilon G$ do:
    Calculate k-shortest-paths from $o$ to $d$
    Calculate the total cost of the path
    Calculate the probability of the path
    while $P_{min}$ > 10% do:
        store Previous Paths = k-shortest-pahts, total costs of the paths, probabilities of the paths
        k = k+1
    else
        P = Previous Paths
return P
```

4.1 *Data Inputs*

The data for the O/D matrix was obtained from a database made available by [7]. Transport demand were aggregated into 48 zones for this research, as shown in Figure 3. Hereby we assume that zones centroids capture the weighted average location of all freight moving to, or from the zone. Transport demand for the year of 2020 under a Base Line Scenario have been used in this research. On the supply side, aggregated transport networks of road, rail and waterways were used to compute travel times and distances. Based on the zone's centroids, road travel times and distances were retrieved with the use of the Google API application (Figure 4). The railway network has been aggregated based on data provided by National Brazilian Railway Agency [1] and the currently available rail connections is represented by the green arcs on 5. As most *network users* experience cargo transfers when using railways, transfer times and costs are al-

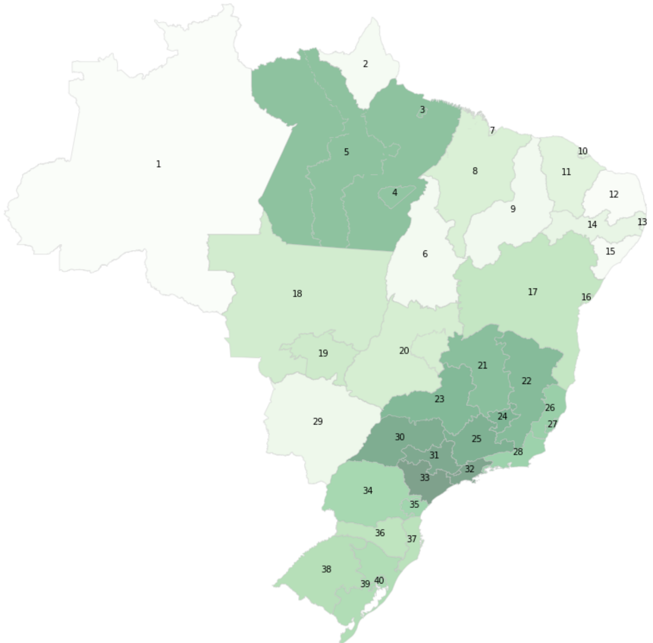


Figure 3. Zoning

ways applied to consider the average pre-end haulage costs (as also proposed by [22]). These values are of course zone specific, and directly related to the geographical characteristics of the zone. A few exceptions apply for the port zones that are connected to each other by a railway, as it is reasonable to assume that no pre-end haulage are implied in this specific situation. Likewise, the railway connections between zones 5 & 8, 25 & 26 and 25 & 29 are not assigned pre-end haulage costs. That is mainly because about 80% of the cargo transported on the Brazilian railways refers to the transport of iron ore generated in zones 5 and 25 and exported via zones 8 and 26 & 29 respectively (information compiled from data obtained from [1]). Lastly, the waterway network was created by clustering ports located close to each together and connecting them between each other, and with the export-import regions. The chosen clustering structure is based on the clustering scheme developed by the Brazilian Port Agency [3], including a total of 12 port clusters. The defined port clusters and their zone numbers can be observed on Figure 7, and their geographical location can be observed on 5.

Figure 4. Aggregated Roadway Network

Figure 6. Supply Networks

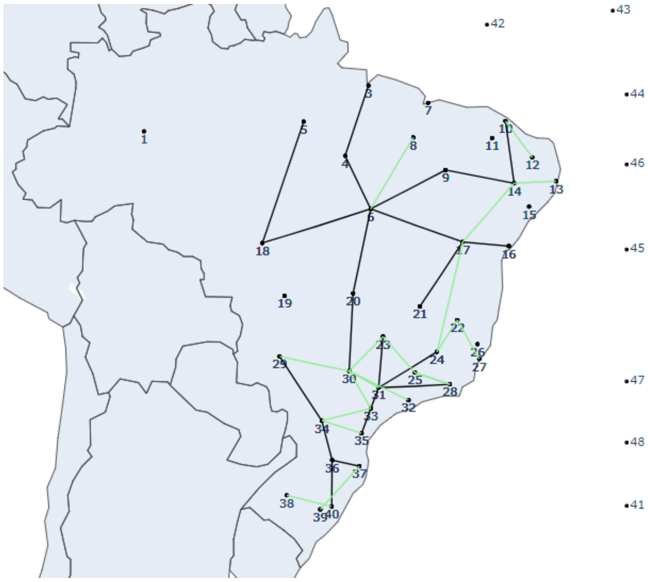
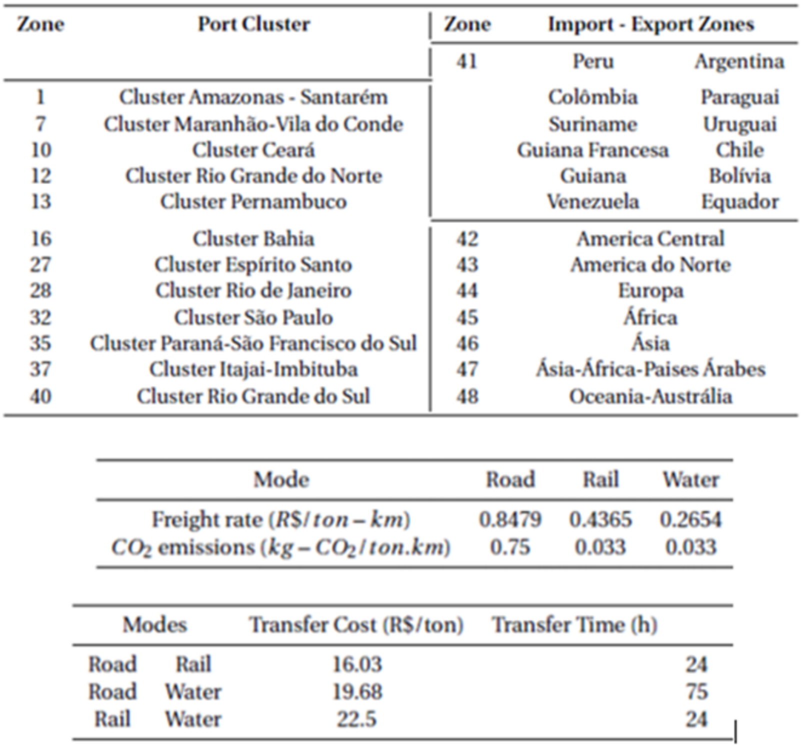


Figure 5. Port Clusters and Railway Network

Figure 7 shows the average values of time and cost of transport and transfer adopted for the model and the average transfer costs and times. Average levels are considered for all attributes and assumed to be the same over the whole network. Lastly, time and cost sensitivity values were obtained from a state-choice experiment conducted by [5] with 13,039 companies. The experiment was conducted with shippers from all over the country, and the estimated global value of time sensitivity (β) is -0.0156 and cost sensitivity (μ) is -0.0169.

The last data input required are the project alternatives for the Action Plans. The development of the Action Plans has been made based on the Railway Infrastructure projects proposed by the Brazilian National Railway Association [1]. The projects proposed have been linked to the zone centroids defined in this research, and the average distance by railway between the zone centroids is considered to be equal to the road distance between the same centroids, as the distance information is not available for several projects. Transfer costs and average road access and egress have been considered by using the same approach proposed for the currently available railway network. Investment costs have been calculated based on on average construction costs of 7 mi R$/km [1] and 25 mi R$/km for medium speed railways (average of 150 km/h as stated by [1]). A total of 34 Action Plans have been proposed (Figure 9) and their impacts have been analyzed under the consideration of railway operation speeds of 28 km/h (current average speed on railways in Brazil), 50 km/h, 100 km/h and 150 km/h.

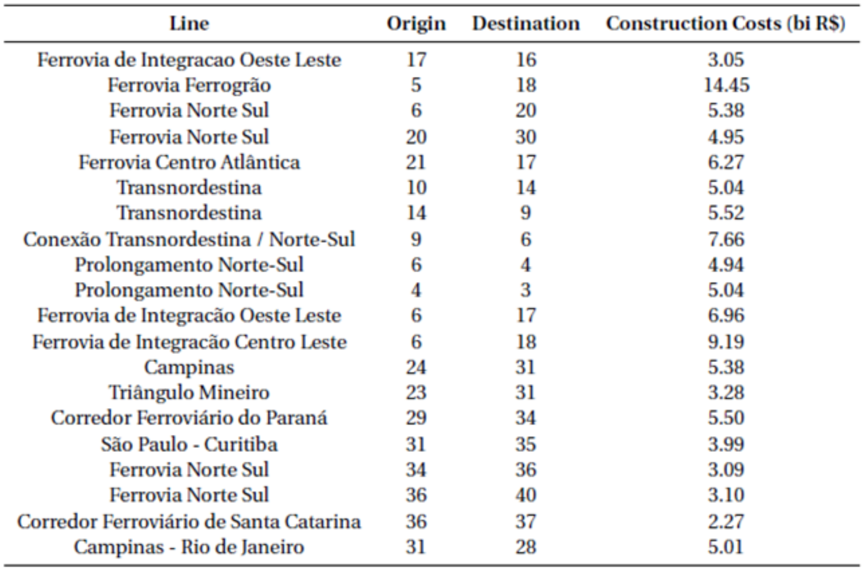


Zone	Port Cluster	Zone	Import - Export Zones	
		41	Peru	Argentina
1	Cluster Amazonas - Santarém		Colômbia	Paraguai
7	Cluster Maranhão-Vila do Conde		Suriname	Uruguai
10	Cluster Ceará		Guiana Francesa	Chile
12	Cluster Rio Grande do Norte		Guiana	Bolívia
13	Cluster Pernambuco		Venezuela	Equador
16	Cluster Bahia	42	America Central	
27	Cluster Espírito Santo	43	America do Norte	
28	Cluster Rio de Janeiro	44	Europa	
32	Cluster São Paulo	45	África	
35	Cluster Paraná-São Francisco do Sul	46	Ásia	
37	Cluster Itajai-Imbituba	47	Ásia-África-Paises Árabes	
40	Cluster Rio Grande do Sul	48	Oceania-Austrália	

Mode	Road	Rail	Water
Freight rate ($R\$/ton-km$)	0.8479	0.4365	0.2654
CO_2 emissions ($kg-CO_2/ton.km$)	0.75	0.033	0.033

Modes		Transfer Cost (R$/ton)	Transfer Time (h)
Road	Rail	16.03	24
Road	Water	19.68	75
Rail	Water	22.5	24

Figure 7. Sources: [17], [6], [13],[4]



Line	Origin	Destination	Construction Costs (bi R$)
Ferrovia de Integracao Oeste Leste	17	16	3.05
Ferrovia Ferrogrão	5	18	14.45
Ferrovia Norte Sul	6	20	5.38
Ferrovia Norte Sul	20	30	4.95
Ferrovia Centro Atlântica	21	17	6.27
Transnordestina	10	14	5.04
Transnordestina	14	9	5.52
Conexão Transnordestina / Norte-Sul	9	6	7.66
Prolongamento Norte-Sul	6	4	4.94
Prolongamento Norte-Sul	4	3	5.04
Ferrovia de Integracão Oeste Leste	6	17	6.96
Ferrovia de Integracão Centro Leste	6	18	9.19
Campinas	24	31	5.38
Triângulo Mineiro	23	31	3.28
Corredor Ferroviário do Paraná	29	34	5.50
São Paulo - Curitiba	31	35	3.99
Ferrovia Norte Sul	34	36	3.09
Ferrovia Norte Sul	36	40	3.10
Corredor Ferroviário de Santa Catarina	36	37	2.27
Campinas - Rio de Janeiro	31	28	5.01

Figure 8. Government Railway Construction Plans

5 CASE STUDY: RESULTS AND INTERPRETATIONS

The performance of the proposed Action Plans has been assessed by compared the results with the reference Case situation (consideration of the current transport infrastructure in Brazil). The results have been analyzed in terms of economic, environmental and social impacts.

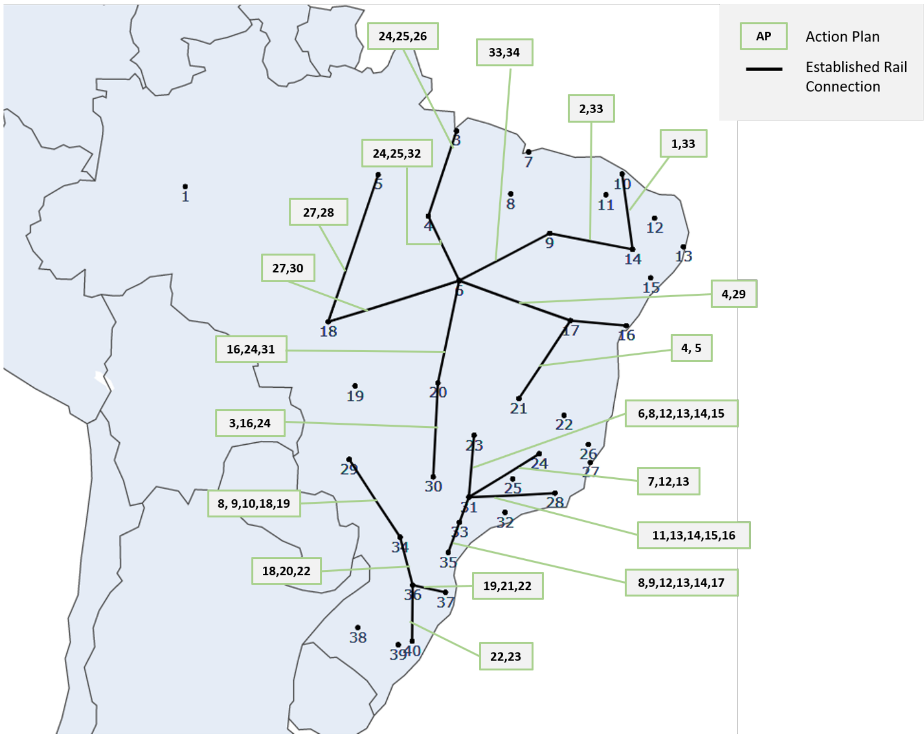


Figure 9. Proposed Action Plans

5.1 *Economic Impacts of Action Plans*

The analysis of the economic impacts of the proposed action plans was done by means analysing their benefit cost ratio (BCR) and the potential attraction of flows on the proposed railway segments. Benefit Cost Ratios were calculated for each of the Action Plans by dividing the gains on the network in terms of total transportation costs (mi R$/year) and time savings (mi R$/year), by the investment costs (thousands R$). In order to monetize the time savings, the value of time of *network users* was obtained by dividing β/μ, resulting in a value of time of 0.92 R$/ton-km. Figure 10 shows that with the given investment costs considered for railway connections of 150 km/h, the benefits of investing in standard railway infrastructure are higher and that increases in speed generate higher BCR (when the investment costs remain the same). Therefore, the conclusion drawn is that railways operating at higher speeds generate higher savings to the network, however, an analysis has to be made regarding the additional investment costs resulted from higher railway speeds.

Additionally, the results lead to the conclusion that Action Plans 2, 4, 5, 6, 10, 11, 18, 19, 20, 29, 31 and 34 are not generating any cost savings to the network. In case of AP's 11, 18, 19 and 20 the short travel distances between the zones does not provide significant benefits to the use of the newly established connections. The rail mode requires the transfer of the cargo, which implies transfer costs and time, as well as pre-end haulage, which does not pay-off in the case of short distance connections. For Action Plans 2, 4, 5, 6, 10, 29, 31 and 34 there is an additional burden to the attraction of cargo on the newly established connections caused by the model assumption of average pre-end-haulage times and distances to the zone centroids. As the zones in the model were defined by production and attraction of cargo, their geographical area varies substantially. The zones where the railway connections were established in the previously mentioned Action Plans present big geographical dimensions, resulting in high average access-egress times for the rail terminals. It is important to keep in mind that the travel times and costs on the alternative paths on the network (namely the alternatives by road and water) also influence the attraction of cargo on the railways. Therefore, the results highlight the challenge of investing on short distance railways, as *network users* become more sensitive to the pre-end haulage and transfer costs/times. Following, the challenges of investing in railways in regions with lower cargo flows is pinpointed by the burden caused by the high pre-end haulage costs.

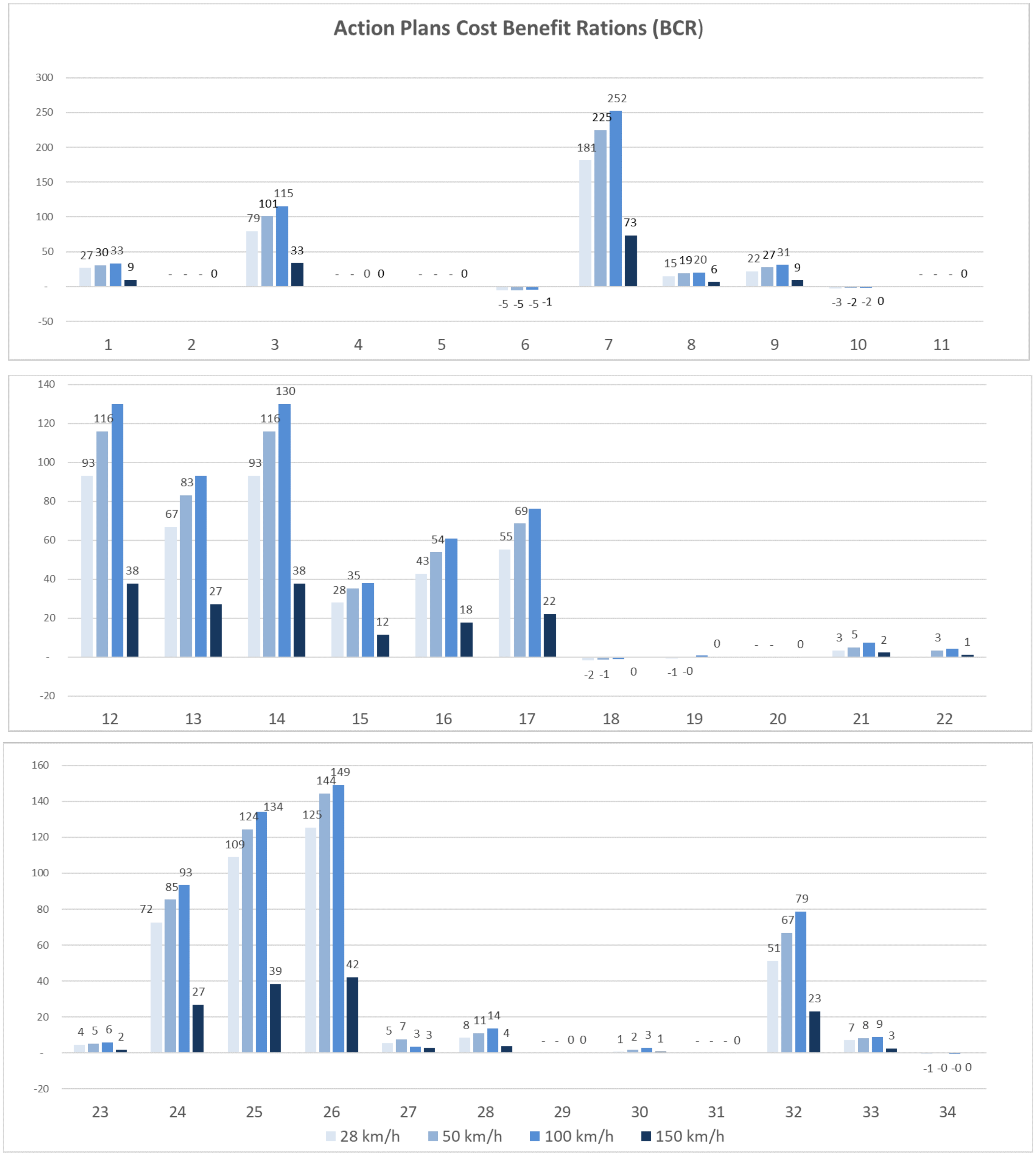
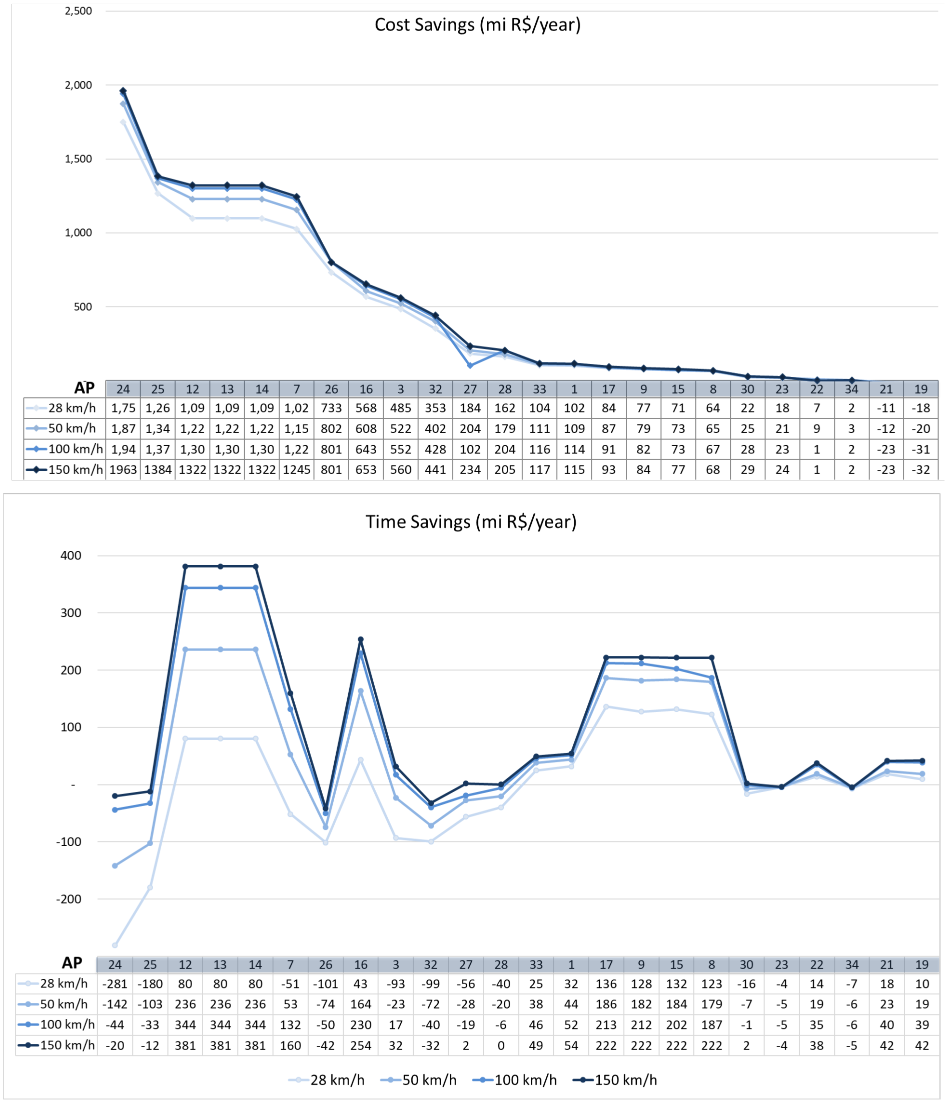


Figure 10. Benefit Cost Ratio of Action Plans under the consideration of different railway speeds

Next, Figure 11 shows how time and cost savings might differ for each action plan. The results have been plotted on a descending order of cost savings, and the actions plans that did not result in any cost and time savings have been removed from the analysis. The graph makes the trade-off between transport costs and times clear. While Action Plan 24 has the highest cost savings for the network, the travel times on the total network actually increase when compared to the Reference Case Scenario. That is mainly a result of the switch of cargo flows from road to rail, that generated cost savings but higher transport times due to factors such as pre-end haulage, lower operational speeds of raiways and transfer times. The additional network savings generated by higher speed railways is also highlighted, as the higher the railway speeds, the higher the time savings.



AP	24	25	12	13	14	7	26	16	3	32	27	28	33	1	17	9	15	8	30	23	22	34	21	19
28 km/h	1,75	1,26	1,09	1,09	1,09	1,02	733	568	485	353	184	162	104	102	84	77	71	64	22	18	7	2	-11	-18
50 km/h	1,87	1,34	1,22	1,22	1,22	1,15	802	608	522	402	204	179	111	109	87	79	73	65	25	21	9	3	-12	-20
100 km/h	1,94	1,37	1,30	1,30	1,30	1,22	801	643	552	428	102	204	116	114	91	82	73	67	28	23	1	2	-23	-31
150 km/h	1963	1384	1322	1322	1322	1245	801	653	560	441	234	205	117	115	93	84	77	68	29	24	1	2	-23	-32

AP	24	25	12	13	14	7	26	16	3	32	27	28	33	1	17	9	15	8	30	23	22	34	21	19
28 km/h	-281	-180	80	80	80	-51	-101	43	-93	-99	-56	-40	25	32	136	128	132	123	-16	-4	14	-7	18	10
50 km/h	-142	-103	236	236	236	53	-74	164	-23	-72	-28	-20	38	44	186	182	184	179	-7	-5	19	-6	23	19
100 km/h	-44	-33	344	344	344	132	-50	230	17	-40	-19	-6	46	52	213	212	202	187	-1	-5	35	-6	40	39
150 km/h	-20	-12	381	381	381	160	-42	254	32	-32	2	0	49	54	222	222	222	222	2	-4	38	-5	42	42

Figure 11. Time and cost savings action plans

Further analysis consisted of understating the changes in rail flows resulted from the establishment of new rail connections in the network. The analysis consisted of understanding which connections attract most cargo, the differences in cargo flow attraction generated by investing in single links or a combination of them and lastly the analysis of where the cargo comes from. Figure 12 shows the attraction of cargo flow on the newly established railway connections for each of the Action Plans. The cargo attractions for the railways under the operation speed of 28 km/h can be observed, as well as the investment cost for each connection, showing the trade-off between required investment and cargo flow attraction of rail segments. It can be observed that connections such as 23-31, 31-24, 4-6 and 20-30 present a great ratio between investment costs and cargo attraction. On the other hand, projects as 5 - 18, 6- 18 and 9 - 6 require large investment costs but are not able to attract substantial amounts of cargo.

Firstly, it was observed that connections 14 - 9, 21 - 17, 31 - 21, 20 - 6 and 36 - 34 did not attract any cargo flows for any of the considered speed of operations of the railways. As previously stated, the main reasons for this are the high

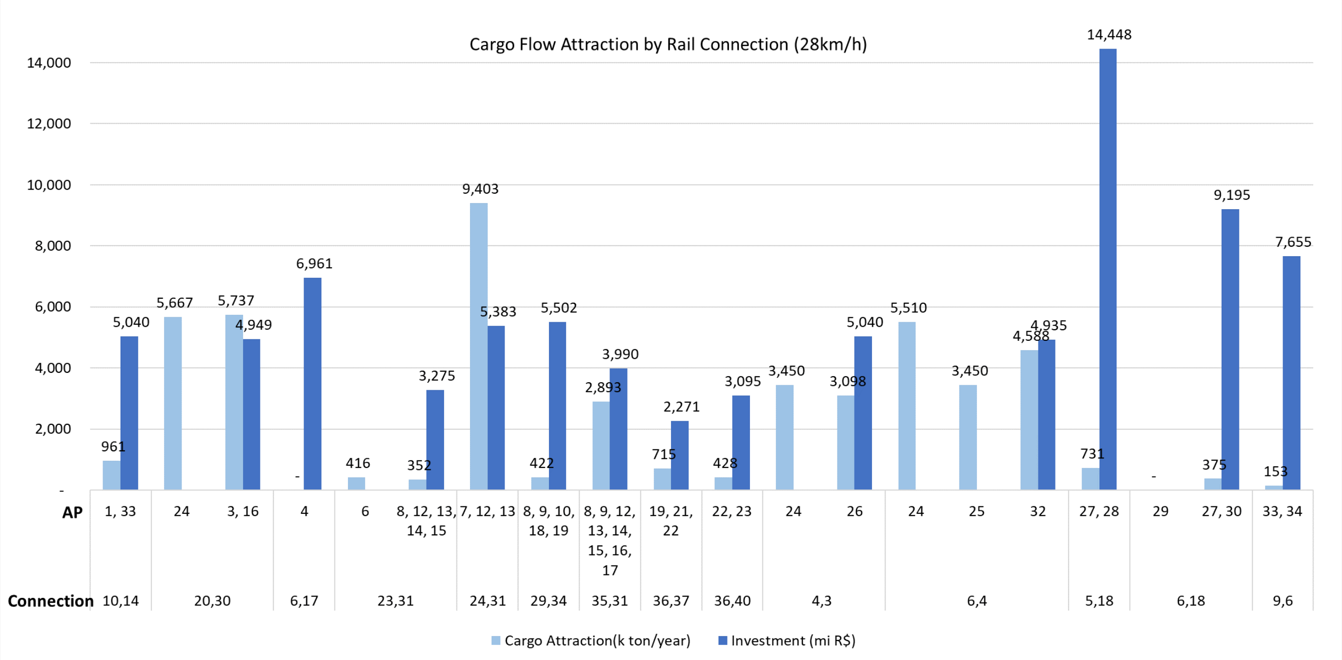


Figure 12. attraction of Flow on Specific Railway Segments based on the Action Plans

impact of transfer costs for short distance connections, and the high costs incurred by pre-end haulage averages for zones with big geographical areas. Additionally, the results have shown that connection 6 - 17 only attracted cargo when the railway speed was set to 100km/h and 150km/h. Likewise, connection 6 - 18 only attracted cargo flows when the speed was set above 100 km/h.

Another observation regarding connection 20 -30 can be made. A reduction in cargo attraction is observed when Action Plan 24 is proposed. That is because cargo is then flowing through arcs 4-3 and 4-6, and reducing the attractiveness of connection 20-30. The assumption of pre-end haulage costs in the model has however hindered the attraction of cargo flow on logistic corridors. This can be observed with connection 20-6 for example, doesn't attract any cargo.

5.2 *Environmental Impacts*

The improvement of the railway network leads to reduction of CO_2 emissions, as railway transport has a lower CO_2 footprint than road transport for the same distance. Therefore, in this research the Action Plans have resulted in a reduction of the environmental impact in the network. Figure 13 shows the reduction in CO_2 emissions and the BCR for the proposed Action Plans, calculated as the reduction in CO_2 divided by the investment costs. It is interesting to see that, while Action Plans 6, 10, 18, 19, 21 an 34 did not generate any transport cost savings to the network, they did reduce the emissions of carbon-dioxide.

5.3 *Social Impacts*

The impacts regarding the social benefits of the Action Plans have been measured in terms of modal split between rail and road. That is mainly because with the reduction of road share, congestion and accident rates are expected to decrease. It is important to highlight that this study did not analyze the effects of pre-end haulage of cargo on the surroundings of railway terminals on the road system.Table 1 shows the share of railway transport (in % of the share) for each of the Action Plans. The additional share (%) expected for each of the action plans is shown, where the Action plans considering the establishment of rail connections with a speed of 28km/h are compared to the rail share of the Reference Case. As no significant differences in the railway shares for the different railway speeds has been observed, only the results for the speed of 28km/h are reported. The results show that there is a direct proportional relationship between investment costs and railway shares.

Algorithm 2 Finding the K loopless shortest paths in a network Yen1971Network

```
Input: a weighted directed graph G = (N, A), the source nodes $o \in N_o$, the target nodes $d \in N_d$,
cost of directed arc from $i$ to $j$ $V_{i,j}$, number of shortest paths to find $k$
Output: k shortest-paths $p_{o,d}$, where k = 1, 2, âĂę , K
for all $o \in N_o$, $d \in N_d$ do
    k = 1, $A = [], B = []$
    Determine the shortest path from $N_o$ to $N_d$ in graph G by using the DijkstraâĂŹs shortest path algorithm
for all k-1 $\forall k \in K$
    try
        for all $P_k, \forall k \in K$ do
            Get the shortest path $P_{k-1}$
           Analyze the path set of nodes $N$ by DS = {o, n$_1^{k-1}, n_2^{k-1}...n_l^{k-1}$}
            If $P_j \in A$ and has the path as the sub path. Then set the weight of the arc from $n$ to
          its immediate neighbor to infinity for P$_j$
            Set sub path $o, n_1^{k-1}, n_2^{k-1}...d$ in $P^{k-1}$ as the root path $R^k$ . Set the path to be determined from n to d is as the spur path, S
            Set the path to be determined
          from n to d as the spur path, S$^k.RemovearcsinR^kfromG$
            Remove arcs in R$^kfromG$
            Compute the shortest path $P_{o,d}^k$ by using the DijkstraâĂŹs algorithm
            If path $P_{o,d}^k$ is found
            Add $R^k$, $S^k$ to form a candidate path for next shortest path. Add path to list B
            From B, move $P_{k-1}$ to A.
        except
        break
```

Table 1. Increase in Railway Shares as a result of the Action Plans

2AP	2Investment (mi R$)	Increase in Railway Shares		2AP	2Investment (mi R$)	Increase in Railway Shares	
3-47-8		28 km/h	(%)			28 km/h	(%)
1	5,040	19.23	0.72	18	8,594	19.94	1.43
2	5,521	19.45	0.94	19	10,864	20.33	1.82
3	4,949	19.55	1.04	20	3,091	19.08	0.57
4	13,226	20.65	2.14	21	2,271	18.91	0.40
5	6,961	19.56	1.05	22	8,457	19.92	1.41
6	3,275	19.06	0.55	23	3,095	18.97	0.46
7	5,383	19.45	0.94	24	20,307	21.91	3.40
8	12,768	20.53	2.02	25	9,975	19.99	1.48
9	9,492	20.00	1.49	26	5,040	19.16	0.65
10	5,502	19.39	0.88	27	23,643	21.78	3.27
11	5,005	19.19	0.68	28	14,448	20.49	1.98
12	12,648	20.60	2.09	29	6,961	19.63	1.12
13	17,653	21.27	2.76	30	9,195	19.87	1.36
14	12,648	21.27	2.76	31	5,383	19.43	0.92
15	7,265	19.67	1.16	32	4,935	19.31	0.80
16	14,322	21.07	2.56	33	18,216	21.27	2.76
17	3,990	19.13	0.62	34	7,655	19.67	1.16

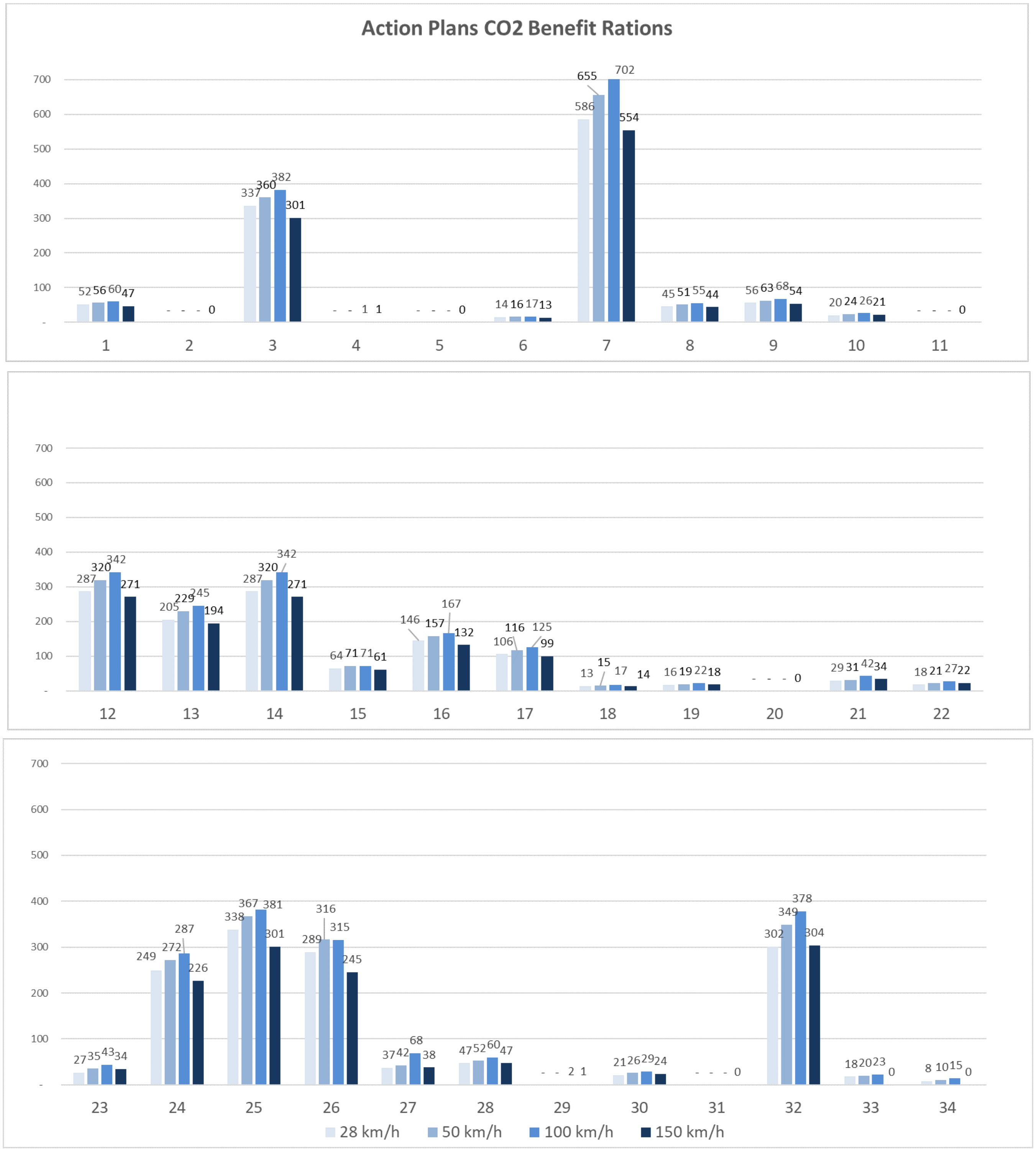


Figure 13. Benefit Cost rations in terms of CO_2 emissions

Even though one could expect the connections with the highest cost savings and reductions in CO_2 emissions to present the best improvements in terms of modal split, that has not been the case. Even though some connections are able to attract substantial amounts of cargo, this cargo can be attracted from other railways, leading to a lower increase in the rail share of the network.

6 CONCLUSIONS

To summarize, from an economical perspective the highest impacts on cost savings can be observed on Action Plans 7, 26, 3 and 32. The best environmental options are considered to be Action Plans 7, 3 and 32. Lastly, from a social perspective it has been observed that higher investments lead to higher shares for the rail mode. The use of choice behavior coefficients for time and cost highlighted the *network users* preferences towards times and costs. The results have shown that even though some Action Plans do not result in significant cost savings for the network (i.e. Action Plans 17, 9, 15 and 8), significant savings can be observed in terms of time savings.

the results have shown that, the higher the railway speed, the higher the benefits for the network (from all perspectives adopted by the model). However, an analysis of the investment costs is required to provide the *network planner* with a clear view of the trade offs between speed increase and investment costs, as this research only assumed two values for the investment costs on railway infrastructures. Finally, this research has shown the importance of pre-end haulage for the attractiveness of railway connections. The assumption that cargo is generated on the centroid of the zones, together with the assumption of average pre-end haulage for railways has shown the importance of the location of railway terminals to attract cargo flows. For zones with low production-attraction of cargo, in which the attraction areas are geographically big the attraction of cargo to the railway is lower than when compared to smaller zones. Lastly, for the short distance rail connections the importance of transfer times and costs has been highlighted.

To finalize, this case study has proven the ability of the proposed model to support policy-makers in their decision-making for multimodal transport infrastructures. The model is able predict the mode and route choices of *network users* and their behavior as a response to network changes. Lastly, it gives great insights for the *network planner* regarding the trade-offs of the proposed investment in terms of economical, environmental and societal impacts.

6.1 *Limitations and Future Research*

Dealing with real-world problems is not an easy task, and several challenges and limitations will be faced by one who is striving to incorporate all possible variables into a model. Additionally, the excess of information not only may distract the modeller from the main goal, but also make the analysis of the results too complex. The main challenge of this research was thus to make the right simplifications and aggregations that enabled an understanding of network freight flows on an aggregate level.

Network and parameters improvements: Due to the lack of commodity specific choice behavior coefficients, this research has used global values and aggregated commodity types as one type of cargo for the flow distribution on the network. For future research, the model can be extended to include a set of products and product specific attributes. Likewise, other appropriate and important avenues for forthcoming studies would be to include constraints on link capacities in the model. This would enable the *network planner* to measure the impacts of network changes for specific commodities and allow for more accurate results. In the same way, the model has aggregated the supply and demand networks. In the case of the demand network, zone centroids were assumed to represent the average weighted location for zone attraction and production. During the case study the implication of using zone centroids could be observed. It could therefore be interesting to consider implementing a gravity model to capture a more suitable location for zone centroids.

Multinomial Logit Model (MNL) and Choice Behavior Coefficients: As previously mentioned, incorporating commodity specific choice behavior coefficients could be beneficial to the network. Another direction for further research is developping additional coefficients (such as alternative specific constants, reliability, among others). In the same manner, the adoption of the MNL model implies that the ratio of choice probabilities of any two alternatives is independent of the presence or absence of a third alternative in the choice set. It is also noted that the MNL is unable to cope with the presence of heterogeneity among choice makers, for which the Nested Logit model or Mixed Logit model would be more suitable. The great advantage of the proposed model is that it does not assume a particular model for the choice behavior set, which gives the opportunity for further improvements in that sense.

Future Uncertainties and Scenario Analysis: The combinations of infrastructure investments has been rather restricted in this research. Not only in the sense of possible rail infrastructure investments which has been restricted to the projects proposed by [1], but also since no other of infrastructure improvements were considered. The modelling of the impacts of medium speed trains (as proposed in the set of projects made available by [1]), and the consideration of the establishment of links not considered in the set of proposed projects are two avenues for future research. Furthermore, the effects of policy regulations such as CO_2 taxation could be tested with the model. Lastly, one may look into the improvement of roadways, and consequently the increase of speed there. The last option would be specially beneficial in combination with capacity restrictions and travel time stochasticity. Lastly, Section **??** pointed out that investments to transport infrastructure are long term investments and there is a need of developing models able to cope with future uncertainties. This research assumed all variables and parameters to be deterministic, however, this assumption might be restrictive in face of uncertainties. Choice behavior coefficients, freight rates, transport times, transfer costs and times, transport demand are all fraught to uncertainties, and more robust results can be achieved when considering them as uncertain. [10] proposed a scenario-discovery approach to cope with uncertainties in container transport. Research could be done to implement such an approach for the hinterland transportation, applicable for all types of cargo.

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