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DALMO DOS SANTOS MARCHETTI

EFFICIENCY IN RAIL SYSTEMS THROUGH THREE DIFFERENT APPROACHES AND CONTRIBUTIONS TO PUSH THE BRAZILIAN RAIL SYSTEM TOWARD HIGH PERFORMANCE

Rio de Janeiro

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A thesis presented to the Instituto COPPEAD de Administração, Universidade Federal do Rio de Janeiro, as part of the mandatory requirements for the degree of Doctor of Sciences in Business Administration (D.Sc.)

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DEDICATION

I leave differently than I entered. Who knows more confident about myself, recognizing that what I have learned is nothing compared to what is left to learn. Who knows more human.

Much was expected, but the achievement seems much greater. Long was the pathway and distant was the arrival point. I will miss both.

I realize the fundamental contributions and insights from teachers, reviewers, researchers and colleagues that boost me forward. What I carry goes far beyond the formal. It's for life. Challenges that seem unobtainable are overcome. It is diving into the unknown and emerging saved.

I dealt with the truth in the purest form I have experienced. I would like this freedom of conscience to be present everywhere in our country. Inside people's heart and inside the Institutions. Undoubtedly, this is the greatest learning of the doctorate.

It was all an enriching experience.

I dedicate this thesis

to my parents, Celia and Arnaldo Marchetti, who gave me the necessary conditions to develop myself according to my own choices and showed me the values of life that are necessary to the building of my dignity.

To my wife, Sheila Marchetti, whose relationship I can summarize in a sentence that I repeat for myself:
"still good that I married you".

To my son, Thiago Marchetti, who in the tenderness of his childhood, when sawing me studying, he often asked me what it was all about and understood why I could not stay with him in those moments (not to mention his birthdays that I missed between 2016-2018, since they always happened on the same date of the POMS International Conference).

DEDICATÓRIA

Saio diferente de como entrei. Quem sabe mais seguro de mim mesmo, ao reconhecer que o que aprendi não é nada diante do que resta a aprender. Quem sabe mais humano.

Muito era esperado, mas o alcançado parece muito maior. Longa era a caminhada e o ponto de chegada. Sentirei muita falta de ambos.

Percebo as contribuições e *insights* fundamentais que te impulsionam para frente. Dos professores, revisores, pesquisadores e colegas. O que levo vai muito além do formal. É para toda a vida. Desafios que parecem inalcançáveis, são enfrentados. É mergulhar no desconhecido e emergir salvo.

Pude lidar com a verdade da forma mais pura que experimentei. Gostaria que essa liberdade de consciência estivesse presente em todos os sítios de nosso país. Sem dúvida, este é o maior aprendizado do doutorado.

Foi tudo uma experiência enriquecedora.

Dedico esta tese

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ABSTRACT

MARCHETTI, Dalmo dos Santos. **Efficiency in Rail Systems through Three Different Approaches and Contributions to Push the Brazilian Rail System toward High Performance**, 2019. 177f. Thesis (Doctorate Degree in Business Administration) - COPPEAD Institute of Administration, Federal University of Rio de Janeiro, Rio de Janeiro, 2019.

This research investigates the efficiency of the Brazilian rail cargo system (SFBC, acronym in Portuguese). The importance of the performance of a rail system to the logistics of goods in countries with large territorial dimensions is recognized. However, its role is secondary in Brazil compared to road transport, representing high economic and environmental costs. SFBC is dedicated to the export of mineral and agricultural bulk where it has a significant capacity for insertion. Meanwhile, the SFBC has an insignificant participation in the internal distribution of goods, which is mostly done in highways, including on longer routes. Consequently, the transport sector in Brazil emits twice as much CO_2 from burning fuels than the world average. SFBC presents characteristics of a medium performance scenario. The performance of the operators is heterogeneous, benchmarking is an outlier, the average efficiency is low, and the average idleness of the sections is high. To discuss the conditions to achieve a high performance scenario is the main contribution of this thesis. Three researches were done to address this issue. The first one is dedicated to estimate the efficiency of the railway concessionaires in Brazil between 2010-2014 by using Data Envelopment Analysis. In a second stage, the significance of selected variables was assessed through Bootstrap Truncated Regression, including the type of the use of the railway track (shared or monopoly), a gap in the literature. The operators were grouped according to the efficiency scores and the type of returns to scale, and measures to increase the efficiency of the clusters were discussed. The second research has the purpose to explain the heterogeneity found in the average efficiency of the different railway systems in the world, the object of researches done between 2000-2016, through a meta-analysis carried out for the first time on railways. For greater robustness, Leave-One-Out-Cross-Validation and Weighted Regression were applied. Public policies including diversification of services and models for assessing efficiency by regulatory agencies were discussed. The third research is devoted to the efficiency of the SFBC railway sections and identifies the significant conditions for high and low performance scenarios by combining the Technique for Order of Preference by Similarity to Ideal Solution and a differential evolution algorithm for estimating the weights of variables in optimized scenarios, another gap in the literature. In a second stage, the significance of the variables selected was evaluated. The research shows that the public manager should push the rail companies toward the transportation of any type of cargo, the diversification of services, the centralized control of the operation, and the sharing of the railway track. The competition and diversification are significant for high performance.

Keywords: railways, Brazil, efficiency, DEA, BTR, meta-analysis, TOPSIS, genetic algorithm.

RESUMO

MARCHETTI, Dalmo dos Santos. **Eficiência em Sistemas Ferroviários Através de Três Diferentes Abordagens e Contribuições para Impulsionar o Sistema Ferroviário Brasileiro em direção ao Alto Desempenho**, 2019. 177f. Tese (Doutorado em Administração) - Instituto COPPEAD de Administração, Universidade Federal do Rio de Janeiro, Rio de Janeiro, ano.

A pesquisa investiga a eficiência do Sistema Ferroviário Brasileiro de Cargas (SFBC). É reconhecida a importância do desempenho de um sistema ferroviário para a logística de mercadorias em países de grandes dimensões territoriais. Todavia, seu papel é secundário no Brasil frente ao transporte rodoviário, representando custos econômicos e ambientais excedentes. O SFBC se mantém dedicado à exportação de granéis sólidos minerais e agrícolas onde apresenta significativa capacidade de inserção, enquanto é inexpressiva sua participação na distribuição interna de bens, majoritariamente realizada pelo setor rodoviário, inclusive em rotas mais longas. Assim, o setor de transporte no Brasil emite o dobro de CO_2 pela queima de combustíveis do que a média mundial. O SFBC apresenta características de um cenário de média *performance.* O desempenho dos operadores é heterogêneo, o *benchmarking* é um *outlier,* a eficiência média é baixa e a ociosidade média das seções é alta. Discutir as condições para alcançar um cenário de alta *performance* é a principal contribuição da tese. Para atingir esse objetivo, foram realizadas três pesquisas. A primeira se dedica à eficiência dos concessionários ferroviários no Brasil no período 2010-2014, com o uso de *Data Envelopment Analysis*. Num segundo estágio, através de *Bootstrap Truncated Regression*, foi avaliada a significância de variáveis selecionadas, incluindo o tipo de uso da via, *gap* da literatura. Os operadores foram agrupados segundo os resultados de eficiência e o tipo de retornos de escala das operações e medidas para o aumento da eficiência dos *clusters* foram discutidas. A segunda pesquisa tem por objetivo explicar a heterogeneidade encontrada na eficiência média de diversos sistemas ferroviários no mundo, objeto de pesquisas realizadas entre 2000-2016, através de uma *metanálise* conduzida pela primeira vez em ferrovias. Para maior robutez, *Leave-One-Out-Cross-Validation* e *Weighted Regression* foram utilizadas. Políticas públicas incluindo diversificação e modelos de avaliação de eficiência por órgãos reguladores foram comentadas. A terceira pesquisa se dedica à eficiência das seções ferroviárias e identifica as condições significativas para cenários de alta e baixa *performance* através da combinação de *Technique for Order of Preference by Similarity to Ideal Solution* e de um algoritmo de evolução diferencial para estimar os pesos de variáveis em cenários otimizados, *gap* da literatura. Num segundo estágio, a significância de variáveis selecionadas foi avaliada. A pesquisa mostra que o gestor público deve empurrar as empresas para o transporte de todo o tipo de carga, a diversificação de serviços, o controle centralizado da operação e o compartilhamento da via. A competição e a diversificação são significativas para a alta *performance*.

Palavras-chave: ferrovias, Brasil, eficiência, DEA, BTR, metanálise, TOPSIS, algoritmo genético

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LIST OF ABBREVIATIONS

3PL	THIRD-PARTY LOGISTICS
3PRLP	THIRD-PARTY REVERSE LOGISTICS PROVIDER
AHP	ANALYTIC HIERARCHY PROCESS
AMB	ADJUSTABLE MEAN BARS
ANTT	NATIONAL LAND TRANSPORTATION AGENCY
ATDF	AVERAGE TRANSPORT DISTANCE OF FREIGHT
BCC	BANKER, CHARNES, COOPER
BNSF	BURLINGTON NORTHERN SANTA FE
BRCS	BRAZILIAN RAIL CARGO SYSTEM
BTR	BOOTSTRAP TRUNCATED REGRESSION
CBTU	BRAZILIAN COMPANY OF URBAN TRANSPORT
CCO	CONTROL CENTRE OF OPERATIONS
CCR	CHARNES, COOPER AND RHODES
CR	CHINESE RAILWAYS
CRITIC	CRITERIA IMPORTANCE THROUGH INTER-CRITERIA CORRELATION
CRS	CONSTANT RETURNS TO SCALE
DB	DEUTSCH BAHN
DE	DIFFERENTIAL EVOLUTION
DEA	DATA ENVELOPMENT ANALYSIS
DEA CCR	DEA MODEL UNDER CONSTANT RETURNS TO SCALE
DEA BCC	DEA MODEL UNDER VARIABLE RETURNS TO SCALE
DEOPTIM	DIFFERENTIAL EVOLUTION OPTIMIZATION
DF	DISTANCE FUNCTION
DFM	DISTANCE FRICTION MINIMIZATION
DM	DECISION MAKER
DMU	DECISION MAKING UNIT
DODF	DIRECTIONAL OUTPUT DISTANCE FUNCTION
DRS	DECREASING RETURN TO SCALE
EA	EVOLUTIONARY ALGORITHMS
EA FAHP	EXTENT ANALYSIS FUZZY AHP

EPL	EMPRESA DE PLANEJAMENTO E LOGÍSTICA S.A.
EV	ELECTRIC VEHICLE
EWM	ENTROPY WEIGHT METHOD
FBS	FREEWAY BUS SERVICE
FEPASA	FERROVIA PAULISTA S.A.
GA	GENETIC ALGORITHM
GDP	GROSS DOMESTIC PRODUCT
GHG	GREENHOUSE GAS
GLS	GENERALIZED LEAST SQUARES
HGTS	HYBRID GENETIC ALGORITHM AND TOPSIS SIMULATION
HSR	HIGH SPEED RAIL
IAHP	IMPROVED ANALYTIC HIERARCHY PROCESS
IRS	INCREASING RETURN TO SCALE
ISM	INTERPRETIVE STRUCTURAL MODELLING
JR	JAPANESE RAILWAYS
LCM	LATENT CLASS MODEL
LOOCV	LEAVE-ONE-OUT-CROSS-VALIDATION
MCDA	MULTI-CRITERIA DECISION ANALYSIS
MCDM	MULTIPLE CRITERIA DECISION MAKING
MDL	MODIFIED DIGITAL LOGIC
MNSGA-II	MODIFIED NSGA-II
MOCO	MULTI-OBJECTIVE COMBINATORIAL OPTIMISATION
MOPSO	MULTI-OBJECTIVE PARTICLE SWARM OPTIMIZATION
MPSS	MOST PRODUCTIVE SCALE SIZE
MTD	MEAN TRANSPORT DISTANCE
NDEA	NETWORK DEA
NDF	NUMBER OF DEGREES OF FREEDOM
NDM	NORMALIZED DECISION MATRIX
NDMU	NUMBER OF DECISION MAKING UNITS
NL	NUMERIC LOGIC
NSGA-II	NON-DOMINATED SORTING GENETIC ALGORITHM
NVAR	NUMBER OF VARIABLES
OLS	ORDINARY LEAST SQUARES
PCA	PRINCIPAL COMPONENT ANALYSIS

PPP	PUBLIC-PRIVATE PARTNERSHIP
PMM	PERFORMANCE MEASUREMENT MODEL
QM	VALUE OF OMNIBUS TEST
RFFSA	REDE FERROVIÁRIA FEDERAL S.A.
RTS	RETURNS TO SCALE
SBM	SLACK BASED METHOD
SD	STANDART DEVIATION
SDEA	SUPER-EFFICIENCY DEA
SE	SCALE EFFICIENCY
SFA	STOCHASTIC FRONTIER ANALYSIS
SFBC	SISTEMA FERROVIÁRIO BRASILEIRO DE CARGAS (BRCS ACRONYM)
SNCF	SOCIETÉ NATIONALE DES CHEMINS DE FER FRANÇAIS
SUR	SEEMINGLY UNRELATED REGRESSION
T	WALD TEST
TE	TECHNICAL EFFICIENCY
$\overline{TE}$	MEAN TECHNICAL EFFICIENCY
TFP	TOTAL FACTOR PRODUCTIVITY
TGV	TRAIN À GRANDE VITESSE
THSR	TAIWAN HIGH SPEED RAIL
TKU	USEFUL TONS X KILOMETERS
TOPSIS	TECHNIQUE FOR ORDER OF PREFERENCE BY SIMILARITY TO IDEAL SOLUTION
TU	USEFUL TONS
UIC	INTERNATIONAL UNION OF RAILWAYS
UP	UNION PACIFIC
VRS	VARIABLE RETURNS TO SCALE
WLS	WEIGHTED LEAST SQUARES

LIST OF SYMBOLS

$\boldsymbol{\theta}$	EFFICIENCY SCORES
$\boldsymbol{\lambda}$	REPRESENTS THE DUAL PROBLEM COEFFICIENTS
$\boldsymbol{\theta_{CCR}}$	EFFICIENCY SCORES ON DEA CONSTANT RETURNS TO SCALE
$\boldsymbol{\theta_{BCC}}$	EFFICIENCY SCORES ON DEA VARIABLE RETURNS TO SCALE
$\boldsymbol{\varepsilon_j}$	VECTOR WITH THE OBSERVATION OF DMU VARIABLES
$\boldsymbol{X}$	INPUTS
$\boldsymbol{Y}$	OUTPUTS
$\boldsymbol{N}$	NORMAL DISTRIBUTION
$\mathbf{A}^{+}$	IDEAL SOLUTION
$\mathbf{A}^{-}$	NEGATIVE IDEAL SOLUTION
$\boldsymbol{d_i^+}$	POSITIVE EUCLIDEAN DISTANCE
$\boldsymbol{d_i^-}$	NEGATIVE EUCLIDEAN DISTANCE

SUMMARY

1 INTRODUCTION

The expansion of the highway infrastructure, the use of the automobile, and the urban sprawl have reduced the use of railway systems in favor of road transport around the world. However, new economic and environmental factors have revitalized the rail transport such as the restriction of using fossil fuels and the control of greenhouse gas (GHG) emissions, the effort to reduce costs, the search for better living conditions and the restriction of using cars in cities, and the impetus toward intermodalism (HARRISON; DONNELLY, 2011; RODRIGUE; COMTOIS; SLACK, 2013).

The technological development and the new transportation policies are at the origin of seeing value again in railways as an option for efficient and sustainable transport. Since the 1960s, the emergence of the High Speed Rail (HSR) technology in Japan, and in the next decade in France, repositioned the fate of rail transport. Technological improvements created faster and more efficient long-distance connections, causing them to be highly competitive with road and air travel (RODRIGUE; COMTOIS; SLACK, 2013). By the 1980s, public policies had been put in place to promote the revitalization of rail transport, especially for cargo. The regulatory models put into practice in the United States and the European Union sought to ensure the best allocation of resources, increase the efficiency, and take back again the market share lost, being one of the pillars of the rail transport resurgence (CARBAJO; DE RUS, 1991; EUROPEAN POLICY CENTRE, [s.d.]; LEGAL INFORMATION INSTITUTE, [s.d.]; WHEAT; NASH, 2006). In the United States, the Staggers Rail Act (US, 1980) arises as a result of the then recent theory of contestable markets developed at the end of the 1970s by Baumol, Panzar and Willig (1982), which was also applied to the ground and air transport sectors in the American market. Guidelines for the development of railways in the European Union were drawn up in the community. Directive 91/440/EEC (EUROPEAN COMMUNITIES, 1991) is aimed at promoting competition and integration between the rail transport systems in Europe, whose measures began to be adopted by the Member States since 2001.

In Brazil, following the external influence, the rail system was developed at the end of the 19th century, expanded, and declined. It went under State control at the end of the 1930s, the administration of the cargo service was separated from that of urban passengers in the 1980s, and the productivity indicators were recovered after the privatization process and concession of the network, previously administered by the state company Rede Ferroviária Federal S.A. (RFFSA), which took place at the end of the 1990s. However, despite the resumption of investment, the increase in the production volume, and the reduction of the number of accidents recorded in the period after the concession (MARCHETTI; FERREIRA, 2012), the SFBC is heterogeneous, presenting different standards of efficiency, and distinct physical and operational characteristics (MARCHETTI; WANKE, 2017). The set of attributes of the Brazilian rail cargo system (BRCS), among them the low average efficiency, the high average idleness of the sections, the low productivity of the railway track, the low diversity of services and types of cargo, no statistical significance as to the type of use of the rail (if shared or in monopoly), and the heterogeneity among the operators, characterizes a medium performance scenario as will be discussed in the third paper of this thesis. This condition suggests to explain the low participation of the rail transport in the transportation modal matrix in Brazil, and the highest participation of the transport sector in emitting CO_2 from burning fossil fuels in Brazil (46%), compared with the global average (23%) (FERREIRA et al., 2016; IEA, 2013). More details on the SFBC are provided in the subsections 1.1.2 and 1.1.3. The greatest challenge of the managers and public administrators in Brazil is to move the SFBC to a high performance scenario.

The federal government, which is responsible for planning in the railway sector, is in the process of discussing and analyzing the early extension of the existing concessions on the basis of Law No. 13,448, of June 5, 2017 (BRAZIL, [s.d.]). Among other aspects, the Law No. 13,448 sets the conditions for the advance extension of concession contracts in the railway sector as long as it is timely requested by the incumbents. The early extension is linked, among other terms, to the inclusion of investments not foreseen in the original contract in order to meet the growth in demand, and the elaboration of a technical study by the incumbent that proves the advantage of extending the current contract compared to holding a new bid. To assess whether the provisions of Law No. 13,448 are able to encourage the concessionaires toward a SFBC high performance scenario is the subsidiary question of this research.

In Brazil, the National Land Transportation Agency (ANTT), responsible for monitoring, regulating, and inspecting the SFBC, does not evaluate the efficiency of the rail concessionaires by methods widely used in the literature, which makes it more difficult to decide for the early extension of existing contracts due to the interest on the part of the public administration. The planning of investments within the framework of the federal government is limited to new concessions (BRAZIL, [s.d.]), and does not present objectively what is the role of the railway network in the transportation sector in Brazil, including which targets it should reach, and what economic results it should offer to society in the long term. Issues such as SFBC's level of average performance, the insertion of rail transport according to the type of cargo, the provision of new services, the entry of new operators, the regional and inter-regional transport of passengers, the level of intermodal operations, and the development of rail corridors for the regional integration have not been systematically planned or addressed in an effective way to change the reality of SBFC's current attributes. The planning of the federal government is highly linked to the construction of new isolated railways (BRAZIL, [s.d.]) on the basis of proposals mostly presented from the export private sector, with a low systemic vision, similar to what happened in the development of the Brazilian system in the late 19th century, that was characterized by a dispersion and isolation of the railways. The North-South Railway, otherwise, planned by the federal government, is a single example of a regional integration railway.

The theme of this research is the efficiency of the railway systems. The objective of the research is to answer the following four questions: What is the efficiency of the SBFC concessionaires? What are the variables and the significant factors for SBFC's efficiency? What are the evidences extracted from previous researches that influenced the average efficiency of different rail systems in the world? What are the conditions required to push SBFC to high performance? Therefore, three independent scientific papers were developed using different databases and methodologies that together allow readers to obtain the evidences and insights that answer these research questions.

The first paper is entitled *Brazil's Rail Freight Transport: Efficiency Analysis Using Two-Stage DEA and Cluster-Driven Public Policies* and deals with the efficiency of the SFBC using Data Envelopment Analysis (DEA), widely applied to evaluate the relative performance of Decision Making Units (DMUs) (MARKOVITS-SOMOGYI, 2011; WANKE; BARROS, 2015). The efficiency of the SFBC concessionaires for the period 2010-2014 was evaluated when a new regulation that sought to boost competition in the system was put into practice. Through the Bootstrap Truncated Regression (BTR) model, in a second stage, the significance of exogenous variables in the performance of the concessionaires was estimated, such as the type of cargo, the gauge (track width), and the type of use of the railway (if shared or in monopoly). The significance of the new regulations on the efficiency of the DMUs (SFBC concessionaires) and the methodological structure itself in two stages were constituted in the gap in the literature. The article also proposed the grouping of the concessionaires into clusters according to their efficiency score and the type of the returns to scale (RTS) of each concessionaire (whether increasing, constant, or decreasing). Public policies to increase the efficiency of each one of these clusters were discussed, such as: increase in scale of operations with expansion of inputs (upsizing); best combination and/or reduction of inputs (downsizing);

and, simultaneously, the adoption of better operational practices, improvement in the railway infrastructure to increase the assets turnover, and upsizing (or downsizing).

The second paper is entitled *Efficiency in rail transport: Evaluation of the main drivers through meta-analysis with resampling* and reveals through a meta-analysis of 21 articles published between 2000-2016 the variables and the factors that explain a significant part of the heterogeneity found between the different efficiency frontiers observed in different rail systems, with distinct characteristics and methodologies applied by the authors. Meta-analysis is a systematic review model from literature supported by statistical methods increasingly adopted in social sciences but, as to our best knowledge, used for the first time to aggregate and contrast results of researches on efficiency frontier of railways. From a systematic review of the articles, the research aimed at obtaining results not identified in each study individually to explain the variance in the average efficiency estimates. Among the findings, the article concludes with an important evidence for the Brazilian market where there is predominance or almost exclusive transport of cargo on the existing rail network. Other conclusions of a methodological nature are also presented and contribute to the best performance of the role performed by monitoring, regulatory and inspection agencies, which should evaluate the efficiency of public services applying methods widely used in the literature. Validation methods were presented regarding the independence of the terms, the independence of the observations, the requirement of normal distribution of the dependent variable, and other potential sources of biases in the results (HIGGINS; THOMPSON, 2004), bringing robustness to the results and becoming a true research finding.

The third paper is entitled *Efficiency of the rail sections in the Brazilian railway system using TOPSIS and a Genetic Algorithm to analyze optimized scenarios* and evaluates the efficiency of the rail sections using a TOPSIS methodology that when combined with a genetic algorithm of differential evolution estimates the weights of the positive and negative TOPSIS variables and simulates the behavior of the scores in the optimized low and high performance scenarios. The use of a genetic algorithm for estimating weights in optimized scenarios was, as to our best knowledge, a methodological innovation. In the literature, it is common to use a genetic algorithm together with the TOPSIS model, but in a different way from the one proposed in the paper. Evolutionary algorithms are usually used to optimize multi-objective functions in different systems or products and the TOPSIS methodology is commonly used in a second stage to rank the optimal solutions found. The use of the railway sections as a unit of analysis also enabled innovative conclusions about the efficiency of the Brazilian rail system because it linked the physical, operational, capacity, and regulation characteristics of the railway sections of the network. By using a Tobit model, the significance of contextual variables selected in each optimized scenario was analyzed, such as the operator, the predominant type of cargo transported, the type of technology used in the operation, and the type of use of the railway section (whether open or restricted). The significant attributes of low and high performance were highlighted. Finally, by analyzing the percentiles of the scores, it was possible to identify the least and most efficient railway sections for each scenario, offering a contribution of an administrative-managerial nature. The reading of the three papers in sequence will allow readers to gather evidences and obtain their own insights on how to leverage the efficiency of a railway system and what mechanisms are needed to drive and push the SFBC into high performance scenario.

This thesis is divided into five parts. The theme, gaps found in the literature, and the questions of the research are presented in Section 1. A contextualization in subsection 1.1 prepares the reader for the papers. From Section 2 to 4 is the development of the research itself, in the format of three scientific papers that complement each other, providing the reader the conditions that explain the efficiency and the significant attributes for SFBC's high performance. In subsections 5.1 to 5.3, the conclusions and recommendations are presented, answering the research questions. In subsection 5.4 the limitations found and the suggestions for going deeper into the knowledge about the efficiency frontier of the Brazilian rail system are discussed. Resulting papers from the thesis are presented in subsection 5.6.

1.1 CONTEXTUALIZATION

The next subsections present how the rail transport first appeared and the development of railway systems in the world. The same analysis was conducted for the Brazilian rail system. Information regarding the market-share of the rail transport in Brazil, and the behavior of the supply and demand of goods transport in the country are also presented to support the research. They prepare the reading of the papers and, next, the conclusions.

1.1.1 The Development of Railways in the World

During the pre-industrial age, sea transportation was the most convenient way to transport cargo and people. The most important cities were coastal cities in the Baltic, North and Mediterranean Seas, and the ports located in the interior of the European continent, such as London, Norwich, Königsberg, Hamburg, Bruges, Bordeaux, Lyon, Lisbon, Barcelona and Venice. The maritime connections were the principal way to commercial exchange and reflected country´s economic strength. The industrial revolution during the 18th and 19th centuries brought significant changes to the transport systems. The emergence of the steam engine, attributed to Watt in 1765, beyond giving great impetus to the maritime systems, introduced the rail system (RODRIGUE; COMTOIS; SLACK, 2013).

The steam engines were widely applied on railways. In 1814, George Stephenson, English mechanical engineer, presented the first project of a steam locomotive, given the start to the railway age. The need of an economic transport of large volumes of cargo, with higher speed and for more distant sites were the main aspects that boosted the project (MUNHOZ, [s.d.]). In 1830, Stephenson constructed the locomotives used in the first commercial railroad for the transportation of coal between Manchester and Liverpool (65 km) (WIKIPÉDIA, [s.d.]).

Railroads were then built in England, Western Europe and North America. The first railway in Japan date 1872. In the United States railroads appeared to first complement the main important systems of channels. Soon, railroads begun to be more efficient than channels and their natural substitute. In the late 19th century, 130,000 km of railways were laid in the United States. Transcontinental railway lines were built in the United States (New York to San Francisco, 1869), Canada (Trans-Canadian Railway, 1886) and Russia (Trans-Siberian Railway, 1904). With the development of the engines, rail networks developed worldwide. Cities sprung up along the railways. Rail services became specialized, offering passenger, cargo and mixed services. The growth of urban population favoured the construction of railways for the public transportation of passengers, and subway systems were built in major European metropolitan areas.

However, with the development of highways in the last century, and an economy focused on the intensive use of the automobile, the conventional rail system reduced its importance (RODRIGUE; COMTOIS; SLACK, 2013). In the sixties, a disruption happened. On October 1st, 1964, the Japanese national railways started the operation of a 515 km standard gauge line (1,435 mm) named the Tokaido Shinkansen, from Tokyo Central to Shin Osaka. Initially designed to operate at 210 km/h, its meaning was that the HSR technology had just born. On September 27, 1981, in turn, the *Société Nationale des Chemins de Fer Français*, the national French railway company, started the operation of the first high speed line between Paris to Lyons, at a maximum speed of 260 km/h. The European HSR was born. More recently, the HSR technology was developed especially in China, who implemented a network more than 21,000 km long (UIC, 2015), and in Korea and Taiwan.

The expansion of the railways reached its height in the 20th century but is still expanding denoting vitality. The rail infrastructure in the world is divided among Europe

(29%), for passenger and cargo services, mainly in Germany, France and Ukraine; Asia and Oceania (26%), intended to meet the major part of the global passenger demand located in Japan, China and India, but also cargo, mainly in China and India; Americas (30%), with the predominant cargo transportation; Russia (9%), mainly for cargo transport, but also passenger services; and Africa (6%), for cargo and passenger transport (UIC, 2015). The HSR technology is present mainly in Asia (75%) and Europe (24%). The highlights are the Japanese, French and German systems and the recent Chinese system. Spain, Italy, South Korea, and Taiwan are other remarkable countries using the HSR technology (UIC, [s.d.]).

1.1.2 The Development of the Brazilian Rail System

The implementation of the Brazilian rail system dates back to the second half of the 19th century. The first rail section was introduced approximately 24 years after the laying of the first commercial railway line in England. Irineu Evangelista de Souza envisioned and built in Rio de Janeiro the Mauá Railroad, a first rail line 14.5 km long and 1.68 m gauge between the port of Estrela at the bottom of the Guanabara Bay, in a location called Raiz da Serra, in the direction of the imperial city of Petrópolis. The Baron of Mauá, as he was known, also participated in drafting or negotiating nine other railroads in Brazil (WIKIPÉDIA, [s.d.]). After incentives from the government initially embodied by Decree No. 101, of October 31, 1835, the Feijó Decree (a letter of exclusive privilege for the construction and operation for a period of 40 years of railway lines between the States of Rio de Janeiro, Bahia, Minas Gerais, and Rio Grande do Sul), and subsequently by Decree No. 641, of July 26, 1852 (BRAZIL, [s.d.]) (granting of privilege for the construction and operation for a period of up to 90 years, exemption of import duties on imported machinery and materials, guarantee of interest on the capital invested, right to expropriate private land and receiving free land grants of national areas without economic use, and safeguarded areas), new railroads were deployed. In the period between the second half of the 19th century and the first half of the 20th century, railroads of different gauges were installed in a dispersed way in the Brazilian territory by private and foreign (English) capital companies. The main economic incentive was to meet the needs of urban centers and the ports with agricultural and minerals products coming from the countryside. In Rio de Janeiro, the main railroads built were D. Pedro II and the North Railway, linking Rio de Janeiro to São Paulo. In São Paulo, a network for transporting coffee to the Port of Santos was deployed, including the main connection between Santos to Jundiaí (São Paulo Railway Ltda) and Jundiaí to Campinas (Companhia Paulista de Estradas de Ferro), and the

Sorocabana, Mogiana, Araraquara, and Northwest of Brazil Railways. The latter crosses the current state of Mato Grosso do Sul until the city of Corumbá on the border with Bolivia. The second railroad implemented in Brazil was the Recife-Vila do Cabo (The Recife and São Francisco Railway Company), in the Northeast Region of the country, which was later merged with the Recife-Paudalho connection (Great Western) and interconnected with the Bahia to São Francisco railroad, giving origin to the northeast rail network. It was intended mainly to meet the needs of the sugar cane industry and to transport imported manufactured products. The Madeira-Mamoré Railway was laid in the Northern Region of the country. The economic function of the railroad was the land transport along the Madeira River of the latex rubber produced in the northern region of Bolivia. With the decline of the international rubber market, the railway succumbed after a truly epic story during its construction due to the difficulties encountered in the jungle where thousands of technicians and workers were decimated by malaria and yellow fever (MUNHOZ, [s.d.]). In the South Region of the country, several railroads were laid, such as Porto Alegre-São Leopoldo (Companhia Limitada Estradas de Ferro de Porto Alegre a Nova Hamburgo), Curitiba-Paranaguá, which at the time was considered impossible to execute due to the abysses, overpasses, and bridges, Mafra-São Francisco do Sul, and Ourinhos-Londrina. According to Munhoz (s.d.), the policy of government incentives for building railroads has brought consequences that persist until today, denoting a lack of a long-term strategy on the part of the imperial government, such as: diversity of gauges, making the operational integration between the railroads difficult; winding and excessive length pathways; and the dispersion and isolation between the rail lines. Many passages without interconnection were subsequently abandoned and roads were opened to replace them. The lack of a systemic integration of the SBFC lasts until today.

The government of Getúlio Vargas, at the end of the 1930s, initiated the process of reorganizing the railways and promoting investments by taking over foreign and national companies that were in a poor financial situation (MUNHOZ, [s.d.]). In the beginning of the 1950s, the system totaled 37,000 km long. Eighteen regional railroads were handed over to the administration of RFFSA, created in 1957. Among the main reasons of taking railways over by the Union included to avoid the interruption of traffic, prevent unemployment, provide operational improvements, promote an administrative reorganization, and recover lines and rolling stock (MUNHOZ, [s.d.]). The state of São Paulo created the Ferrovia Paulista S.A. (FEPASA) in the 1970s to administer approximately 5,000 km of railways, subsequently made federal and included in the national privatization program. In 1984, similar to what was already happening in Europe, there was the administrative and accounting separation of the cargo and urban passenger transport services, thus excluding RFFSA from urban transport. The Brazilian Company of Urban Transport (CBTU) was responsible for providing urban services. Finally, at the end of the 1990s, the RFFSA privatization process was carried out with the entire rail system being granted to seven concessionaires for a period of 30 years, in most cases, and the operational assets were leased. The economic rationale for the privatization was to reduce the public operational deficit, attract financial and administrative capital from the private sector, to improve governance, and to increase investment in the rail sector to meet the demand expansion. Furthermore, the Federal Government granted to Vale Company, within its privatization process, the exploitation of the Vitória to Minas and Carajás Railways. Subsequently, RFFSA was closed through Decree No. 6,018, of January 22, 2007 (BRAZIL, [s.d.]). Other concessions were granted by the federal government such as Ferronorte (North Network Railway) in 1990 and the North-South Railroad in its north stretch in 2004. The current Brazilian network has about 29,000 km with few sections widely used and many almost without use. The Central and South part of the North-South Railway, in the centre region of the country, was recently granted to Rumo Logistics in March, 2019.

1.1.3 The Role of the Rail Sector in Freight Transport in Brazil

Brazil has a freight transport matrix that is unbalanced (EPL, 2016) when compared with countries of large territorial dimensions. Road transport has the highest market-share in Brazil, including for long distances routes. This imposes high economic and environmental costs, impacting the cost of transportation, the cost of distribution of inputs and of industrial products (the logistic cost), and the emission of pollutants. Figure 1.1 shows the freight transport matrix in Brazil. Data from Empresa de Planejamento e Logística S.A. (EPL). Created in 2012, EPL is a the state company focused on the Brazilian logistic planning, integrating roadways, railways, ports, airports, and river transport. SFBC covers 15% of the demand for cargo transportation, while road transport meets 65%. In the United States, for example, the ratio of rail transport in the modal network is approximately 43% and the road transport is approximately 32% (ILOS, [s.d.]). In Brazil the cost of logistics is estimated at 11.7% of the gross domestic product (GDP) while in the United States it is around 8.3% of the GDP (ILOS, [s.d.]). The transport (services) sector in Brazil is responsible for the largest share of CO_2 emissions from the combustion of fuels (46%). The average participation of these emissions from transportation is smaller in the world, reaching about half of what is registered for Brazil, 23% (FERREIRA et al., 2016; IEA, 2013).

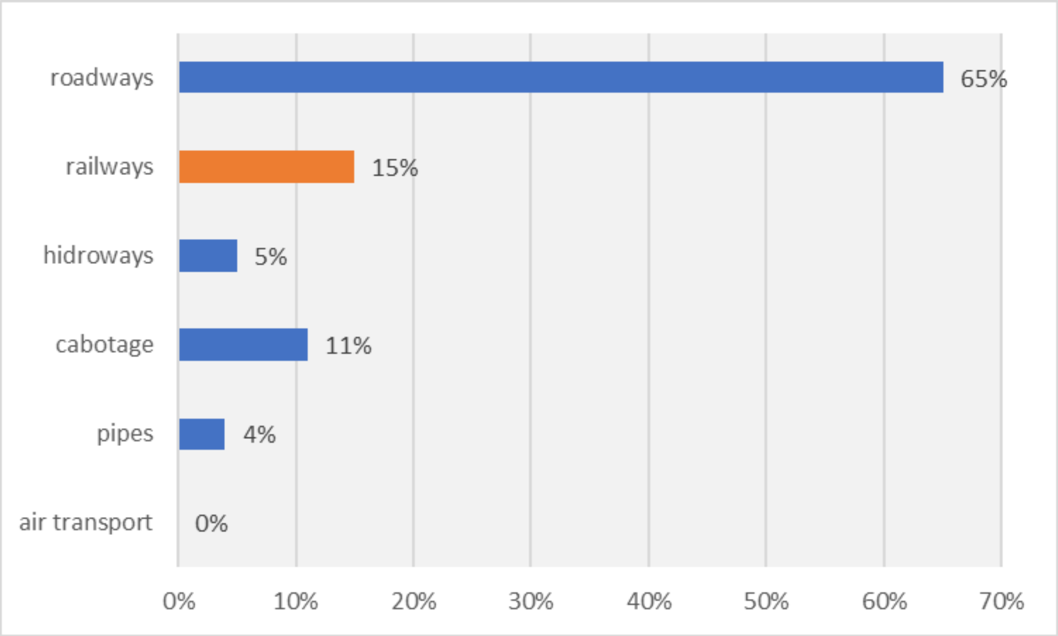

Figure 1.1: Freight transport matrix in Brazil, 2015

Source: EPL (2016)

Figure 1.2 presents the demand transported on railways in 2015 per type of cargo. The demand transported by SFBC, approximate representation of supply, is concentrated in mineral and agricultural bulk, nearly 95% of the total. General cargo and liquid bulk represent only 5% of what is transported on the Brazilian railways (EPL, 2016).

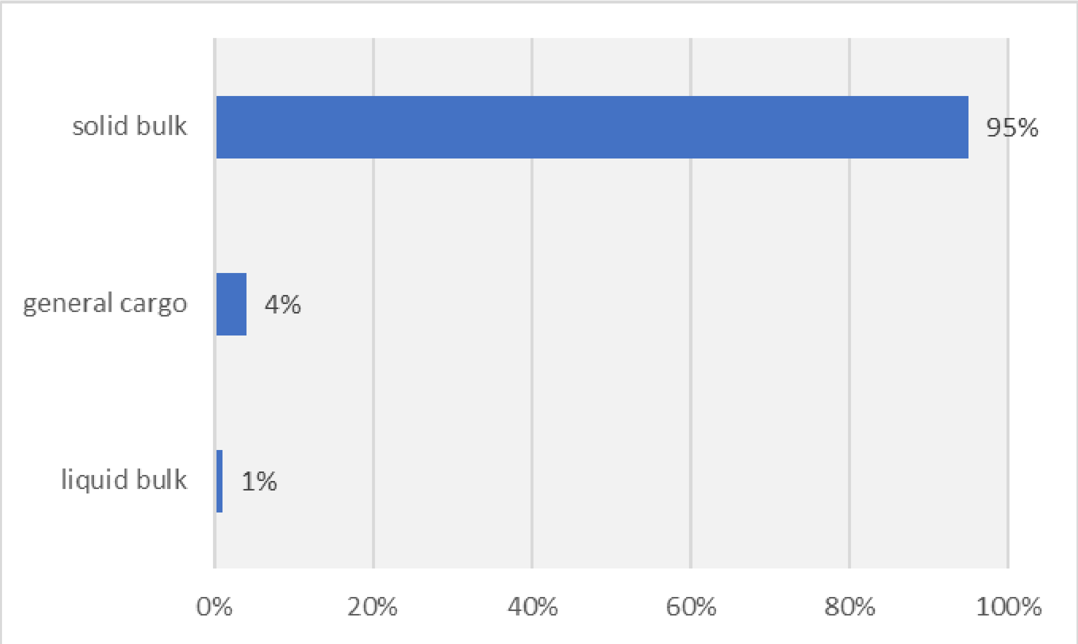

Figure 1.2: Rail sector transport per type of cargo in Brazil, 2015

Source: EPL (2016)

The demand for transportation in Brazil, in turn, is diverse, reflecting the country's economic complexity, being the largest portion represented by the transportation of general cargo (1,292 billion tons.km). The relative importance of the type of cargo in the demand for transportation is presented in Figure 1.3.

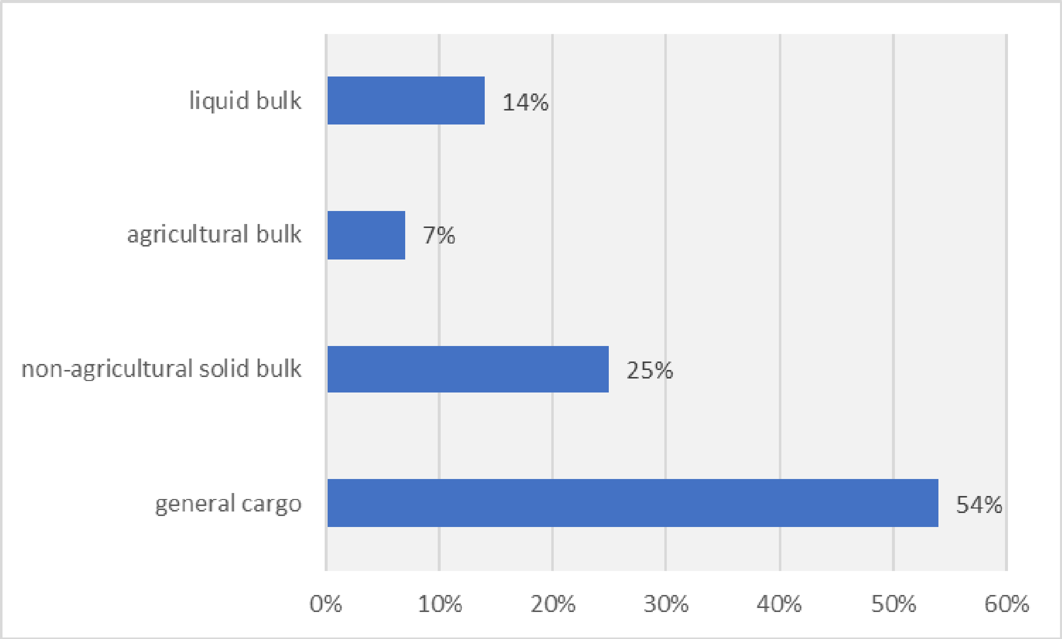

Figure 1.3: Transport demand per type of cargo in Brazil, 2015
Source: EPL (2016)

The insertion of the rail modality according to the type of cargo and the comparison with the highway mode of transport is presented in Figure 1.4. The concentration of the rail system in bulk transport is evident. 49% of non-agricultural solid bulk, 30% of agricultural solid bulk, and only 1% of general cargo are transported on the Brazilian railways, while highway transport is more diverse, and more focused on general cargo and agricultural bulk. The transport of bulk liquid is performed mostly by the waterway mode and by pipes, being the most well balanced in the country.

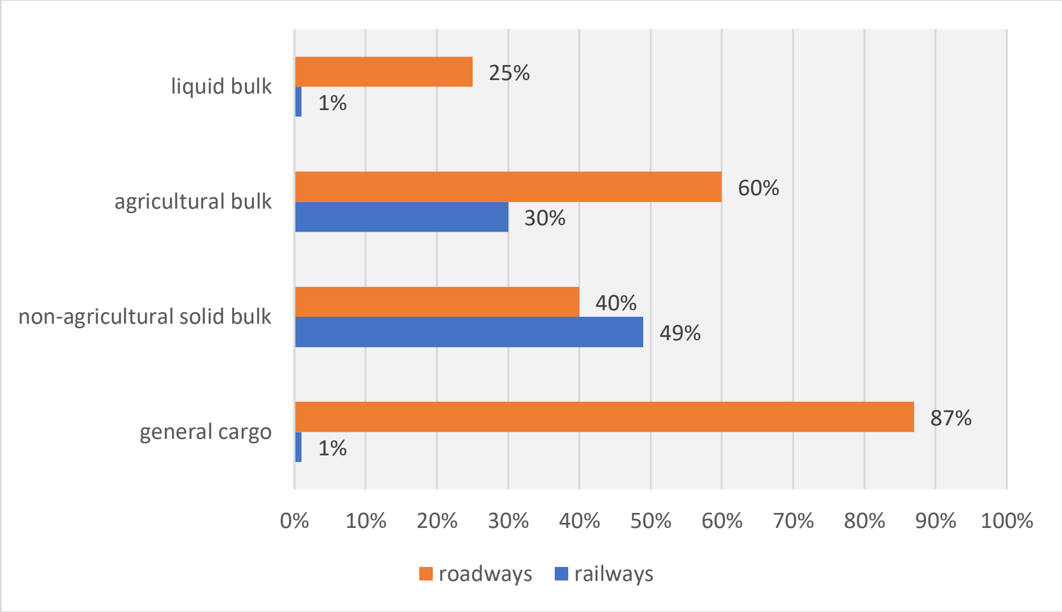

Figure 1.4: Road, and rail transport market-share per type of cargo in Brazil, 2014

Source: ILOS (s.d.)

When focusing on road transport, it can be seen that the consolidated long-distance inter-regional transport along longer routes, with an average length of 1,305 km, using larger capacity vehicles, and with the participation of independent drivers, accounts for 69% of everything that is transported on Brazilian highways. It uses 54% of the diesel consumed in the roadway mode (cargo transportation) in the country (ILOS, [s.d.]). Figure 1.5 shows the relative production and the relative consumption of diesel fuel depending on the type of road transport.

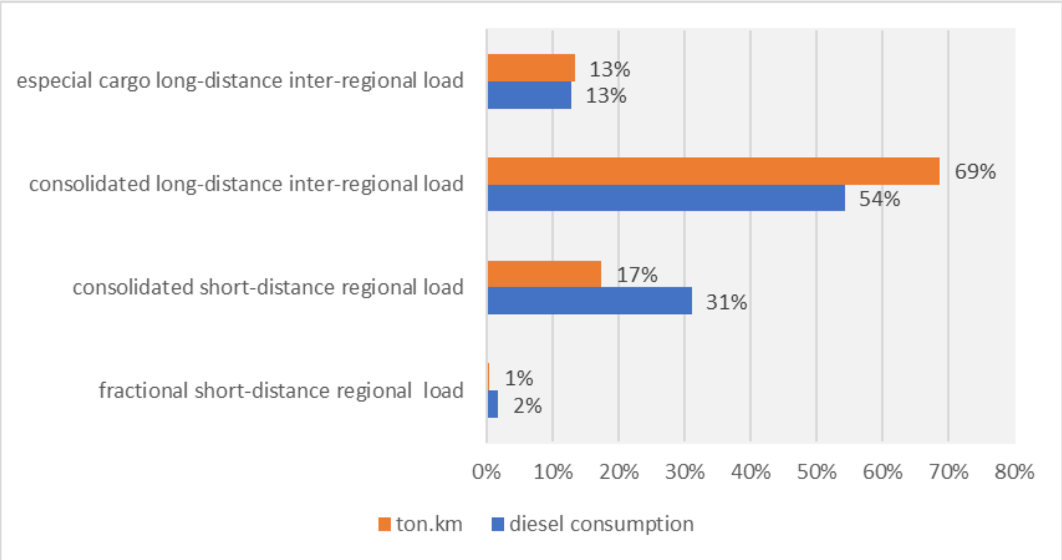

Figure 1.5: Ton.km, and diesel consumption per type of the road transport in Brazil, 2014

Source: ILOS (s.d.)

In Brazil the rail sector concentrates on handling the export of solid bulk with a low diversification of scope where it dedicates about 95% of its offer. Road transportation participates in the handling of solid bulk, but mainly in meeting the internal demand of general cargo for inter-regional long distances. This is where the highest economic costs are concentrated and the largest amount of emission of pollutants from the consumption of diesel are registered. Public policies should attempt to change this reality in the long term in order to balance the Brazilian transport matrix, reducing the cost of transportation, the logistics cost, and the emission of pollutants from the transport sector in the country. In addition to expanding the participation in bulk transport, a new action that lead to a significant participation of the railway sector in general cargo transportation will be decisive since it has a marginal participation in the main demand for transportation in the country (EPL, 2016).

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2 1ST PAPER: “BRAZIL'S RAIL FREIGHT TRANSPORT: EFFICIENCY ANALYSIS USING TWO-STAGE DEA AND CLUSTER-DRIVEN PUBLIC POLICIES”

"BRAZIL'S RAIL FREIGHT TRANSPORT: EFFICIENCY ANALYSIS USING TWO-STAGE DEA AND CLUSTER-DRIVEN PUBLIC POLICIES"

Abstract

This paper uses Data Envelopment Analysis to assess the efficiency of Brazilian rail concessionaires between 2010 and 2014, when new competitive regulations were introduced. In a second stage, a Bootstrap Truncated Regression was used to test the significance of exogenous variables on concessionaire performance: main type of cargo, track gauge, railway operation type (shared infrastructure or monopoly), in order to address an important gap in the literature. Secondary data came from the National Land Transport Agency (ANTT). The findings have significance for broad-gauge track commodities transport, while shared-infrastructure operations had no significance on efficiency, despite regulator incentives. Well directed regulations must encourage concessionaires to increase efficiency, particularly through incentives for agricultural and mineral commodities carried on the broad-gauge track characteristic of North and Center-West Brazil. Public policies designed to boost cluster efficiency are presented, addressing options such as upsizing, downsizing and resizing inputs, restructuring, best management practices and infrastructure upgrades.

Keywords: Efficiency; Railway; Brazil; DEA; Regulation

2.1 INTRODUCTION

Due to the continent-sized dimensions of Brazil, cargo transport plays a leading role in lowering transportation costs. It is vital for servicing economic boundaries, increasing the competitiveness of companies and enhancing the well-being of the population through more affordable access to materials (industrial inputs) and goods. However, the cargo transport matrix is unevenly structured in Brazil, with the road mode accounting for some 67% and railways accounting for around only 18% (ILOS, 2014). There are several reasons behind this situation going back many years, which outside the scope of this paper. It is important to stress only that the road mode has higher total costs per unit carried than rail, for long-distance transport of goods (ILOS, 2014), which is typical in Brazil. Brazil's cargo transport matrix structure holds the entire nation hostage to higher environmental and transport costs than countries with better balanced cargo transport matrixes (EPE, 2014). It is, thus, a matter of strategic importance for Brazil to achieve an even balance for its transport mode matrix from the standpoint of the competitiveness of its companies and of the transport industry as a whole, lowering their overall CO2 emissions (JITSUZUMI; NAKAMURA, 2010). It will be important to make good use of potential reductions in outlays on logistics (freight fees, inventory, cargo handling costs and overhead) resulting from more intensive use of alternative means of transport with greater cargo unit capacity (railways and waterways) to service new economic frontiers in the Center-West, North and Northeast Regions, as well as areas with more mature economies.

For the transport infrastructure to function efficiently, its operations must be efficient in terms of sector-specific benchmarks. Thus, when presenting the topic of this survey – the cargo-carrying efficiency of Brazilian rail concessionaires – one must address the development of the Brazilian economy. For comparative measurements of concessionaire efficiency, a commonly used technique was used, which is Data Envelopment Analysis (DEA) (ILOS, 2008; MARKOVITS-SOMOGYI, 2011; WANKE; BARROS, 2015a). The model allows comparative assessments to be made of a set of Decision-Making Units (DMUs), to see which of them are on the efficiency boundary of the production possibility set and thus benchmarks for other inefficient DMUs. From a methodological standpoint, this paper contributes in the second stage with an analysis using Bootstrap Truncated Regression (see Methodology) of the significance of contextual variables in DMU performance. The selected variables are 'predominant cargo' (agricultural commodities, mineral commodities or assorted cargo), track gauge (broad or metric) and 'type of operation' (shared infrastructure or monopoly). This paper seeks to shed light on the conditions that would boost the efficiency of Brazilian rail transport by evaluating, among other aspects, whether the regulatory incentives designed to boost competition offered by the ANTT after 2011 (see on Brazilian Rail Freight Context) — particularly shared track use — have been significant for DMU efficiency, which is the main gap in the literature. Proposed public policies focused on groups of concessionaires (clusters) with similar performances are presented.

The reminder of this paper is organized as follows. Initially, in Section 2.2, the Brazilian Rail Freight Context is presented. Section 2.3 shows a review of the literature on railway efficiency, indicating the gap in the literature. Section 2.4 describes the methodology used to analyze the data. Section 2.5 comprises a detailed description of the database and our findings, including the significance levels of the selected contextual variables on DMU efficiency. Additionally, rail concessionaires are clustered by performance and a proposal is made for public policies (item 2.5.4), and outliers are discussed (item 2.5.5). Section 2.6 concludes the discussion and presents the constraints of the survey, and suggestions for future projects focused on the development of Brazil's rail freight sector.

2.2 BRAZILIAN RAIL FREIGHT CONTEXT

Although Brazil's rail freight network is around 29,000 km long (ANTT, 2015), it is used unevenly because while some segments carry heavy traffic every day, others are underutilized, if at all. Twelve concessionaires operate this network under a concession model that is controlled by the private sector from standpoint of the capital ownership. A minority share of capital is owned by the public sector (in America Latina Logística S.A., merged with Rumo Logistics S.A. in 2015, 8%; Vale, 5%; and VLI, holding that controls FCA and FNS, 16%), though this does not affect capital control. This private sector control was firmed up through the concession award process for rail transport systems in Brazil between 1996 and 1999 (MARCHETTI; FERREIRA, 2012).

As to concessionaire performance, how is this impacted by the regulatory environment? More than half of the concessionaires haul mainly agricultural commodities and ores (ANTF, 2015; ANTT, 2015). The predominant track gauge is metric (58% of the DMUs) and 25% of the DMUs in the sample operate shared infrastructure with other operators. The concessionaires are clustered mainly in South and Southeast Brazil (58%). Furthermore, most (74%) of the cargo carried on the system is considered tied to the rail sector (i.e., not subject to economic competition from other means of transport). Mineral commodities are particularly important (iron ore, other ores and coal) (ANTF, 2015). Transportation of agricultural commodities (soybeans, soy bran, and maize), although typically carried by rail, is open to competition from other haulage options, especially the road mode with its economic and environmental externalities.

The key regulatory framework consists of provisions set forth in the concession agreements, supplemented by resolutions published by the National Land Transport Agency (ANTF, 2015; ANTT, 2015; ILOS, 2008; MARCHETTI; FERREIRA, 2012; WANKE; BARROS, 2015a). Some operating indicators present growth rates higher than those of the Brazilian economy for the period (ANTF, 2015). Important indicators include transport output in useful tons x kilometers (TKU), investments (in Brazilian reais), reduced rate of accidents (number of accidents recorded by number of trains and kilometers travelled) and cargo shipped in useful tons (TU). However, from 2011 onwards, the regulatory framework for the Brazilian rail sector was gradually altered in an attempt to include provisions for competition in the network, in order to provide users with greater benefits. Outstanding efforts include the removal of regulatory obstacles to facilitate the penetration of rail concessionaires into third-party networks, the setting of new contractual production (TKU), and safety targets and, subsequently, implementation of a methodology for calculating the rates to haul each type of cargo (MARCHETTI; FERREIRA, 2012). Resolutions promulgated by the ANTT in 2011 (Resolutions Nº 3,694, 3,695 and 3,696/2011) (ANTT, 2011a, 2011b, 2011c) seek both to boost supplies for the concession system and encourage intra-mode competition; this can be achieved mainly through regulating mutual traffic and right-of-way operations and setting segment production targets for each concessionaire to allow third-party use of idle capacity.

The modifications to the regulatory framework fostered competition in the network while curtailing the monopolistic powers of the incumbents, culminating in Decree Nº 8,129, promulgated on October 23, 2013, which established the policy of free access to the federal rail sub-system, based on the European model (BOGNETTI; FAZIOLI, 1999; KUMBHAKAR et al., 2007; LOIZIDES; TSIONAS, 2002). Rail sector regulations made provision for separating the concessions for operating rail infrastructure and the rendering of rail transport services. Viewed as a whole, the regulations altered the organizational structure of rail operations from a monopoly regulated by segments to a contestable market with no barriers to entry, despite the existence of the economies of scale that are typical of natural monopolies and the multiplicity of services in the network.

The alterations being implemented suggest that the grantor authority was dissatisfied with the results of the administrative mechanisms put in place by the rail concessionaires. These included the exercise of monopolistic power in price management, control of supply quantities, and quality of service at a level often harmful to users. Although disputed by operators, these conditions were the principal reason for removing barriers to entry for new operators (MARCHETTI; FERREIRA, 2012). Concerns built up regarding whether the assessment of these matters was scientific and whether the selected remedy (regulatory actions) was the right choice for boosting the efficiency of Brazilian rail freight operations.

In this context, we present the main questions underpinning the proposal to generate expertise: How efficient are cargo-carrying rail concessionaires in Brazil? Which operators are on the efficiency frontier? What exogenous factors affect the efficiency of these companies? Do shared-infrastructure operations impact concessionaire efficiency? What public policies could be adopted to boost efficiency? This survey seeks to solve a practical problem for the Brazilian economy by delineating the conditions needed to boost rail freight efficiency and thereby enable lower transport costs in the supply chain of products being transported in Brazil.

Table 2.1 presents the rail concessionaires that constitute the sample for this survey. In addition, the predominant cargo, rail network track gauges, regions serviced by each of the concessionaires and type of operation, whether shared infrastructure (with more than one operator) or monopoly (exclusive to a single operator) are listed. Concessionaires with shared operations addressed by this survey were ALL.P, which encompasses the operations of ALL.N, MRS and FCA; the EFC, which includes the operations of FNS; and FNS, which encompasses the operations of VALEC, handled by VLI on behalf of VALEC.

Table 2.1:
Brazilian rail concessionaires, predominant cargo, area(s) of operation, predominant network track gauges and type of operation.

ALL.N	América Latina Logística Malha Norte S.A. (Rumo)	agricultural commodities	CW	broad	monopoly
ALL.O	América Latina Logística Malha Oeste S.A. (Rumo)	assorted cargo	CW* and SE	metric	monopoly
ALL.P	América Latina Logística Malha Paulista S.A. (Rumo)	assorted cargo	SE	broad*	shared
ALL.S	América Latina Logística Malha Sul S.A. (Rumo)	assorted cargo	S* and SE	metric	monopoly
EFC	Estrada de Ferro Carajás - VALE S.A.	mineral commodities	N* and NE	broad	shared
EFVM	Estrada de Ferro Vitória a Minas - VALE S.A.	mineral commodities	SE	metric	monopoly
FCA	Estrada de Ferro Centro-Atlântica S.A. (VLI)	assorted cargo	CW, NE and SE*	metric*	monopoly
F.OES	Estrada de Ferro Paraná Oeste S.A.	agricultural commodities	S	metric	monopoly
FNS	Ferrovia North South - VALEC S.A. (VLI)	agricultural commodities	CW, N* and NE	broad	shared
FTC	Ferrovia Tereza Cristina S.A.	mineral commodities	S	metric	monopoly
FTL	Ferrovia Transnordestina Logística S.A.	assorted cargoes	NE	metric	monopoly
MRS	MRS Logística S.A.	mineral commodities	SE	broad*	monopoly

*predominant, CW=Center-West, N=North, NE=Northeast, SE=Southwest; S=South;
Broad = 1.60 m wide; Metric = 1.00 m wide.

2.3 LITERATURE REVIEW

Several surveys of analysis of transport system operating performance have been conducted using the non-parametric DEA model. Markovits-Somogyi (2011) compiled 69 applications reported in the literature, finding that the methodology is widely used to assess companies in the transport sector through a wide variety of methodological nuances. The application of DEA has diversified to studies of airports (33%), ports (30%), public transport (15%) and railways (13%). Only five studies (7%), however, were conducted in South America, the majority being focused on Europe, Asia and North America. The inputs used were selected mainly from labor (employees) and capital (production equipment) factors. The outputs normally employed refer to operating results and/or financial earnings of transport companies (MARKOVITS-SOMOGYI, 2011).

Focusing on rail infrastructure and the methods employed by researchers, George and Rangaraj (2008) used super-efficiency DEA (SDEA) to assess the performance of railway zones in the Indian network in terms of the best-performing zones and efficiency trends. Yu (2008), Yu and Lin (2008) and Doomernick (2015) used the network DEA (NDEA) approach to assess production efficiency, service efficacy, and efficacy of 40 European railway systems, 20 passenger and cargo railways selected from all over the world, and the high-speed passenger transport systems of Asia and Europe, respectively. Efficient input deployment was compared with system efficacy using the production and service provider models. The production phase output was construed as input for the service provider phase in the model proposed by the authors; moreover, the efficacy of the systems is viewed as the final outcome between the two evaluation models. Through the NDEA, Yu (2008) and Yu and Lin (2008) felt that the methodology offered greater insights into the sources of inefficiency for purposes of upgrading system performance. Doomernick (2015) found the most efficient systems in the sample, together with the factors contributing to high output performance.

Shi, Lim and Chi (2011) et al., Guzmán and Montoya (2011), Kabakasal, Kutlar and Sarikaya (2013) and Doomernick (2015) not only analyzed efficiency scores using DEA or NDEA models to assess progress in productivity among railways in the US and Spain: they also looked at selected railways elsewhere in the world and high-speed rail passenger transport systems, respectively, by analyzing the progression of the Malmquist Index. Management productivity and technical efficiency gains were also examined during the period under analysis. Shi, Lim and Chi (2011) examined the productivity gain factors for each US railway, concluding that the leader was Burlington Northern Santa Fe (BNSF) followed by Union Pacific (UP). Guzman and Montoya (2011) analyzed the gains in productivity among Spanish railways that would explain the corporate movements subsequent to the period under analysis. Kabakasal, Kutlar and Sarikaya (2013) studied the efficiency scores of 31 railway companies worldwide and concluded that total factor productivity (Malmquist Index) increases by only 0.03% for the entire period analyzed.

Oum, Pathomsiri and Yoshida (2013) used the non-parametric Directional Output Distance Function (DODF) method together with compound social efficiency indicators to assess DMU efficiency, concluding that railways are socially more efficient than airlines. The classic DEA (CCR and BCC) models were used by Bil (2013), Hilmola (2007) and Bhanot and Singh (2014). Bil (2013) evaluated the overestimation of efficiency scores through DEA models, Pareto efficiency analyses, and the assurance region method, finding that the results are sensitive to the models used but probably have no major impact on the final conclusions (efficiency rankings). Hilmola (2007) assessed the efficiency of European railways and their adaptation to shrinking demands, concluding that railways in the Baltic nations Estonia and Latvia are the most efficient for cargo transport. Bhanot and Singh (2014) presented the performance indicators for Indian railways carrying containers in the period following the lifting of the monopoly held by the CONCOR state-owned enterprise. They found lower efficiency of the state-owned company during the period under analysis.

Several researchers have analyzed the relationship between the variables used to explain efficiency scores. Hilmola (2011) used a linear regression after applying the DEA model and analyzed the relationship between the efficiency scores of the public transport system and the extent of use of individual transportation (automobiles) in major cities. He found a significant relationship between low automobile use and higher efficiency values for public transport systems. Kutlar, Kabasakal and Sarikaya (2013) used the Tobit Regression to check which DEA model outputs were significant for the efficiency scores found in the DEA CCR and DEA BCC models, finding that the outputs were more significant in terms of explaining allocative efficiency. Chen (2014) analyzed the efficiency of the Freeway Bus Service industry in Taiwan (FBS) after the arrival of the Taiwan High-Speed Rail system (THSR), assessing the significance of several contextual variables on the scores with a Tobit Regression. Chen found that the arrival of THSR improved the long term efficiency of the FBS, despite the decline of industry competitiveness since 2007 (motivated by technological changes), the significance of market-share, and the increase in management outlays on the performance of incumbents. Kabakasal, Kutlar and Sarikaya (2013), in his turn, utilized a Panel Regression to analyze the influence of DEA models on the output variable, concluding that CCR models provide more meaningful explanations for some output variables than BCC models. Also through the Tobit Regression, Wanke and Barros (2015a) investigated the effects of contextual variables (location and cargo type) on the efficiency scores found in the Brazilian rail freight industry using Distance Friction Minimization (DFM). They concluded that regulatory authorities must consider two groups of companies in terms of funding with different interest rates for infrastructure investments: one focused on iron ore transport and the other on hauling agricultural commodities and general containerized cargo.

Additional parametric methods have been used to assess railway efficiency. Bogart and Chaudhary (2013), Crafts, Mills and Mulatu (2007) used Total Factor Productivity (TFP). Bogart and Chaudhary (2013) measured Indian railway growth between 1874-1912, concluding that had surpassed the expansion of American, British and Spanish railways. Crafts, Mils and Mulatu (2007) analyzed the productivity of British railways between 1852 and 1912, finding management problems related to collusion and entry barriers. Leunig, Mulatu and Crafts (2008), in another study, utilized TFP to assess whether British railways were well-managed at the beginning of the twentieth century. They concluded that rail companies were not well-managed a hundred years ago and were hampered by costs inefficiencies and low growth of TFP levels. Neither competition nor regulation were effective. Dodgson (2011) used TFP to analyze the productivity of British railways between 1893-1912 in a disaggregated model (locomotives, wagons, permanent way and traffic), concluding that productivity growth in the period was slow, despite the growth in transport in the first decade of the twentieth century and additional consumption of inputs. Couto and Graham (2008) used Stochastic Frontier Analysis (SFA) to analyze the efficiency of the European railway industry between 1972-1999, finding an average efficiency loss of 15% due to rising costs from technical (6.5%) and allocative (7%) inefficiency. Kumbhakar et al. (2007) utilized Latent Class Model (LCM) and panel data of 17 European railways between 1971-1974, claiming the input orientation model (cost function approach) is to be preferred after the European directives to increase profits and reduce losses (in 1984, decentralized methods of management by sector, separating accounts and costs of each business segment and, in 1991, competitive access to infrastructure based on the principle of vertical disintegration between infrastructure and operations). They found the input model to be more appropriate in countries such as Spain, Portugal, Greece and Ireland, while the output orientation model (revenue function approach) is more suited to railways in Switzerland, Luxembourg, Norway, Denmark and Sweden. Loizides and Tsionas (2002) proposed a General Index to assess the evolution of the productivity of 10 European railways between 1969-1992, including special circumstances between different countries in the sample (economies of scale, regulatory restrictions, etc.), not considered in the TFP model. For that reason, Loizides and Tsionas (2002) utilized a Seemingly Unrelated Regression (SUR) using different coefficients for each railway. The results showed a declining trend. Only German and British railways showed a positive evolution (technical change), while the others generally presented room for improvement in terms of productivity.

Some authors have compared parametric with non-parametric methods. Graham (2008), for instance, compared efficiency scores with DEA and TFP, noting a similarity between the efficiency ratings, despite differences in terms of economies of scale among urban rail companies. Technological elements that comprise firm-specific technology include system control types, economic vibrancy of the city, and population density, all of which influence the productivity of urban rail companies. Others authors sought to interpret inefficiency sources and have devised methods to optimize subsidy levels and assess the relationship between subsidy and efficiency. Concerned about the cuts to productivity incentives in subsidized companies and the struggle for financial support caused by increasing energy and labor costs, Mallikarjun, Lewis and Sexton (2014) applied a non-oriented NDEA to assess the efficiency of 24 public rail systems in the US during 2001-2010. To evaluate the relationship between inefficiency and subsidy, Mallikarjun, Lewis and Sexton (2014) utilized a censored Tobit Regression and a Generalized Least Squares (GLS) Regression with bootstrapping in order to address concerns regarding non parametric efficiency scores. It turned out that highly subsidized systems were, on average, less efficient in terms of operational costs and revenues than less subsidized systems. In other words, there is a statically significant negative relationship between efficiency and subsidy in the sample studied. Jitsuzumi and Nakamura (2010) used DEA in conjunction with the cost-efficiency model suggested by Farrell (1957) and Debreu (2012) to analyze the causes of inefficiency in Japanese railways. They proposed a method to calculate the optimum level of subsidy to compensate for regional disparities. They found that some railways had received subsidies beyond the values presented by the proposal model, suggesting that the methodology could benefit public authorities.

Table 2.2 presents the literature review.

Table 2.2:
Literature Review.

Author (s) and year	Purpose of the Study	#DMUs	Method (s)	Country of the Study	Inputs mentioned	Outputs Mentioned	Contextual Variables
George, S. A. and Rangaraj, N. (2008)	Performance in railway zones	16	DEA and SDEA	India	Operating costs, tractive effort	ton.km, passenger.km	--
Hilmola, O-P (2007)	Efficiency and productivity of European cargo railways	25	DEA CRS	EU	Employees, locomotives, wagons, line length	tons	--
Yu, M-M (2008)	Efficiency and efficacy of 40 railways (2002)	40	DEA and NDEA	World	Employees, wagons, line length, passenger cars, passenger trains.km, cargo trains.km	ton.km, pass.km, passenger trains.km, cargo trains.km	Income (GNI) and population density
Yu, M-M and Lin, E.T.J. (2008)	Production efficiency, service efficacy and technical efficacy of 20 selected railways (2002)	20	NDEA CRS	World	Employees, wagons, line length, passenger cars, passenger trains.km, cargo trains.km	ton.km, passenger.km, passenger trains.km, cargo trains.km	Income (GNI) and population density
Shi, F.X. et al (2010)	Productivity and technical efficiency of Class I railways (2002-2007)	42	DEA and Malmquist Index	US	Employees, locomotives, wagons, fuel consumption, line length, materials consumed	Revenues/ton.km	--
Guzman, I. and Montoya, J.L. (2011)	Efficiency of Spanish railways between 1910-1922	18	DEA (VRS) and Malmquist Index	Spain	Tractive effort, seats available, available cargo capacity, distance travelled	Revenues	--
Hilmola, O-P (2011)	Assessment of public transport in major cities (railways and others)	43	DEA (CRS) and Linear Regression	World	Population and population density (small DEA); and proportion of jobs in downtown area, GDP/inhab, urban population+ jobs density (large DEA)	Bus.km/hec, tramway.km/hec, VLT.km/hec, metro vehicle.km/hec, train.km/hec or bus.km/inhab, tramway.km/inhab, VLT.km/inhab, metro vehicle.km/inhab, train.km/inhab	--
Bhanot, N. and Singh, H. (2012)	Performance of rail container operators	18	DEA (CRS and VRS)	India	Employees, wagons, cargo terminals, transhipment equipment, containers	ton.km, net profits	--
Kutlar, A. et al (2012)	Performance of passenger and cargo rail companies	31	DEA (CRS and VRS) and Tobit Regression	World	Employees, locomotives, wagons, operating cost, line length and passenger cars	Revenues, passengers, passengers/km, tons, ton/km	--
Bil, J. (2013)	Relevance of overestimation of efficiency	23	DEA (CRS, VRS and SBM)	EU	Employees, wagons, line length, passenger cars	ton.km, passenger.km	--
Kabakasal, A. et al (2013)	Efficiency in railway companies	31	DEA (CRS and VRS), Panel Regression and Malmquist Index	World	Employees, locomotives, wagons, operating cost, line length and passenger cars	Revenues, passengers, passengers/km, tons, ton/km	--

Table 2.2. Continued**.**

Author (s) and year	Purpose of the Study	#DMUs	Method (s)	Country of the Study	Inputs mentioned	Outputs Mentioned	Contextual Variables
Oum, T.H. et al (2013)	Social efficiency of railways and airlines on the domestic market	27	DODF	Japan	Employees, operating cost, capital cost, time travel	Passenger.km, life-cycle CO_2	--
Doomernick, J.E. (2014)	Production efficiency and service efficacy of HST systems	48	NDEA (CRS and VRS) and Malmquist Index	World	Line length, seats available, seats.km	Seats available, passenger.Km, passengers	--
Wanke, P. and Barros, C.P. (2015)	Drivers in the railway operator industry	90	DFM and Tobit Regression	Brazil	Employees, locomotives, wagons, fuel consumption	Investment, revenues, ton.km,	Location and cargo type
Bogart, D. and Chaudary, L. (2013)	TFP estimates for Indian railways between 1874 and 1912, whose growth topped that of American, British and Spanish railways	NA	TFP	India	Employees, fuel consumption, line length, capital inventory variations	ton.km, passengers.km	--
Chen, C.C. (2014)	Efficiency of the bus industry after the arrival of the Taiwan High-Speed Rail system (THSR)	192	DEA, Malmquist Index and Tobit Regression	Taiwan	Number of buses, number of drivers, fuel consumption	Passengers.km	GDP, Market share, bus operator diversification, outlays on sales, overhead and assets
Crafts, N et al. (2007)	Productivity of British railways between 1852-1912	61	TFP	UK	Capital, employees, coal consumed	Passenger trains. Miles, ton.miles (ores), ton.miles (other cargoes)	--
Couto and Graham (2008)	Analysis of technical (management) and allocative efficiency (sub-optimal scale)	30	SFA	EU	Mean wages costs, costs of materials and energy/ trains.km, equipment (capital inventory)	Passenger.km, ton.km (or pass train.km, cargo train.km)	--
Crafts, N. et al. (2008)	Performance of the major British railways in the beginning of the XX century	280	TFP	UK	Capital, employees, coal consumed	Passenger trains.miles, ton.miles (ores), ton.miles (other cargoes)	--
Dodgson, J. (2011)	Performance of the British railways in the end of the XIX century, disaggregating the results in different activities	100	TFP	UK	Employees, fuel, materials and capital	Passenger trains.miles, revenues	--
Graham, D.J. (2008)	Efficiency estimates comparisons between parametric (TFP) and non-parametric (DEA) models	89	TFP and DEA	UK	Employees, fleet capacity (seats) and line length (km)	Passenger cars.km/year	Control systems, subsidy level, environmental externalities (GDP/C and population density)

Table 2.2. Continued**.**

Author (s) and year	Purpose of the Study	#DMUs	Method (s)	Country of the Study	Inputs mentioned	Outputs Mentioned	Contextual Variables
Kumbakar, S.C. et al. (2007)	Efficiency of 17 European railways applied in Panel Data	391	Input and output DF, LCM (mixed)	EU	Energy consumption (kcal), employees and capital (wagons capacity in tons and passenger cars capacity in seats)	Tons/km, passenger/km	Dummies: HSPEED (high speed train services existence), D8494 and D9194 (European directives for improvement of financial performance)
Loizides, J. and Tsionas, E.G. (2002)	Assessment of the productivity growth of 10 European railways during 1970-1992 considering their different characteristics (heterogeneity)	240	DF and SUR	EU	Employees, fuel (electricity, diesel and lubricants), capital (assets, wagons and equipment)	Passenger.km, tons.km	--
Jitsuzumi, T. and Nakamura, A. (2010)	Inefficiency causes on Japanese railways (1998-2003) and optimum subsidy level method	318	DEA and Cost-based model	Japan	Assets, employees, operating costs (except wages, taxes and depreciation)	Passenger.km, tons.km	Transport density (passengers.km/line length)
Mallikarjun, S. (2014)	Relationship between subsidies and performance of US urban railways between 2001-2010	240	NDEA and censored Tobit Regression and GLS Regression with bootstrapping	US	Operating costs (1º stage), vehicle.miles (2º stage), revenue.miles (3º stage), passenger.miles (4º stage)	Vehicle.miles (1º stage), revenue.miles (2º stage), passenger.miles (3º stage), fare revenue (4º stage)	Population density, GDP/C, number of stations, available fleet, total lines length

DEA = Data Envelopment Analysis; DFM = Distance Friction Minimization; DODF = Directional Output Distance Function; NDEA = Network DEA; SDEA = Super efficiency DEA; TFP = Total Factor Productivity; SFA = Stochastic Frontier Analysis; LCM = Latent Class Model; DF = Distance Function; SUR = Seemingly Unrelated Regression; GLS = Generalized Least Squares.

The analysis of the efficiency of rail freight system operations using various DEA models in conjunction with other methods has been addressed by several surveys involving cargo and passenger railways worldwide. However, such surveys of Latin America are sparse, perhaps justified by the smaller relative share held by the rail mode in the transport matrixes of these countries. We believe our assessment of the efficiency of rail concessionaires in Brazil through classic DEA CCR and DEA BCC models, followed by a Bootstrap Truncated Regression at a second stage, constitutes a methodological structure never before used to assess the efficiency of Brazilian rail concessionaires and the impact of selected contextual variables on operator performance. Moreover, the significance of the type of operation (shared infrastructure or monopoly) on concessionaire performance after the process to foster competition in the rail network implemented by ANTT in 2011 onwards, has also not been explored and therefore represents a gap in the literature. Importantly, the answers to the questions listed earlier (i.e., What is the efficiency of railway cargo concessionaires in Brazil? Which operators are on the efficiency borderline? What exogenous factors affect corporate efficiency? Do shared infrastructure operations impact concessionaire efficiency? What public policies could be adopted to boost efficiency?) also constitute findings that could contribute to the formulation of specific public policies for the improved efficiency in Brazil's rail freight sector. Finally, the paper differs from Wanke and Barros (2015a) in two major aspects. The first relates to methodological framework; the second, the analysis of efficiency of the DEA models combined with scale efficiency (SE) and the type of return to scale (RTS) of the DMUs, thus allowing concessionaires to be divided into specific homogeneous groups (clusters) with public policies targeting each of them, moving ahead in terms of the proposals presented in (WANKE; BARROS, 2015a).

2.4 METHODOLOGY

The methodology is structured into three sections. The first section addresses classic DEA efficiency evaluation models, the DEA CCR and DEA BCC models which constitute the first stage of efficiency evaluation. Next, the evaluation methodology of scale efficiency (SE) is presented, as well as definition of type of return to scales (RTS). The third section explains the methodology used in the second stage – Bootstrap Truncated Regression (BTR) – to assess the significance of selected contextual variables in DMU efficiency.

DEA methodology has been used to define benchmarking strategies (JITSUZUMI; NAKAMURA, 2010), due to the characteristic of defining, for each inefficient unit, subgroups of efficient units that constitute the peer set in order to indicate lines of action for making previously inefficient organizations (DMUs) efficient.

2.4.1 Classic DEA Models

Data Envelopment Analysis is a non-parametric model introduced by Charnes, Cooper and Rhodes (1978) (CHARNES; COOPER; RHODES, 1978), based on the seminal work of Farrell (1957) (FARRELL, 1957), which extended the concept of productivity to efficiency. The purpose of DEA models is to identify and measure relative efficiencies among several production units, Decision-Making Units, defined through efficiency scores. The methodology applies linear programming methods to construct a non-parametric frontier for the data, where efficiency measurements are estimated in relation to the frontier (COOPER; SEIFORD; TONE, 2006). The linear programming model seeks to maximize unit efficiency, expressed as the ratio between outputs and their respective weights and inputs and their respective weights, by comparing the efficiency of the specific unit with the performance of a group of similar units. Units attaining 100% are rated as efficient and serve as peers for those scoring less than 100%. Efficient DMUs (score = 1) will necessarily be located on the production possibility frontier. Less efficient or inefficient DMUs (score < 1) are located some distance from the frontier. The greater the distance from the frontier, the less efficient the DMU.

2.4.1.1 DEA CCR Model

The DEA CCR model is the classic model whose set of production possibilities is based on the hypothesis of constant returns of scale, meaning the DEA model under constant returns to scale (CRS) conditions, where proportional input growth will produce proportional output growth. The model in its dual form (1 to 4, below) is described as follows (COOPER; SEIFORD; TONE, 2006). In the dual formulation known as envelope, $[X]$ represents the inputs, $[Y]$ represents the outputs, $[\theta]$ represents the efficiency scores and $[\lambda]$ represents the dual problem coefficients. The coefficient $[\lambda]$ is non-negative (4). The following index $[_o]$ refers to the observed DMU_o, with its inputs $[x_o]$ and outputs $[y_o]$. The DEA CCR efficiency measurement is known as the Overall Technical Efficiency.

$$\min_{\theta,\lambda} \theta \qquad (1)$$

Whereby:

$\theta.\ x_o - X.\lambda \geq 0$ (2)

$Y.\lambda \geq\ y_O$ (3)

$\lambda\ and\ \theta \geq 0$ (4)

2.4.1.2 DEA BCC Model

Banker, Charnes and Cooper (1984) fine-tuned the DEA CCR model for the variable returns of scale (increasing or decreasing) hypothesis, referring to it as the DEA BCC model, meaning the DEA model under variable returns to scale (VRS) conditions. They formally added an additional restriction on the dual DEA CCR model, as follows:

$\sum_{j=1}^{n} \lambda_j = 1$ (5)

This constraint means that only convex linear combinations of the production possibilities set are on the efficiency frontier, forming a convex envelope that encompasses all data. The output-driven linear programming model is presented below (DEA BCC model, envelope form, output-driven), where $[h]$ represents the efficiency scores:

$\underset{h,\lambda}{\text{Max}}\ h$ (6)

Whereby:

$X_o\ \geq X.\lambda$ (7)

$h.Y_o \leq Y.\lambda$ (8)

$\sum \lambda = 1$ (9)

$\boldsymbol{\lambda}\ \geq 0$ (10)

In addition to constraint (9), mentioned in the DEA BCC model definition, each coefficient $[\lambda]$ is non-negative (10). The DEA BCC efficient frontier reflects so-called Pure Technical Efficiency, which indicates the ability to deploy the best management practices (BOGETOFT; OTTO, 2011). Inefficiency measured in the DEA BCC model (1 – DEA BCC efficiency score) translates as an indicator of management inefficiency (KUMAR; GULATI, 2008), which means inefficiency in organizing inputs or managing outputs.

2.4.2 Scale Efficiency (SE) and Type of Returns to Scale (RTS)

The scale efficiency (SE) of a DMU is given by the ratio between the efficiency scores of the DEA CCR and DEA BCC models, namely $SE = \frac{\theta_{CCR}}{\theta_{BCC}}$, varying between 0 and 1. It measures the impact of scale size on DMU productivity operations, or the ability to generate more outputs per inputs used. When the SE ratio is equal to 1, the DEA CCR and DEA BCC model efficiency scores coincide (RTS is constant) and the DMU operates at the optimum scale. If $0 \leq SE < 1$, the operations scale is inefficient. The scale inefficiency is given by the expression [(1-SE)/100]. Efficiency measured through the DEA CCR model (overall technical efficiency) may be broken down into efficiency measured through the DEA BCC model (pure technical efficiency) and scale efficiency (SE) (BOGETOFT; OTTO, 2011).

There are different ways to define the type of the RTS (SEIFORD; ZHU, 1999). The return to scale may be defined through an inspection of the sum of the weights [λ] resulting from the DEA CCR model for each DMU. If the sum of the weights attributed by the DEA CCR model to each of the DMUs is 1, the scale returns are constant; this is called the Most Productive Scale Size (MPSS). Should this sum be less than 1, than the RTS is increasing (Increasing Return to Scale or IRS) and the scale efficiency is rated as sub-optimum. If the sum is greater than one, the RTS is decreasing (Decreasing Return to Scale or DRS) and the scale efficiency is rated as above optimum (KUMAR; GULATI, 2008; WANKE; BARROS, 2015b).

2.4.3 Bootstrap Truncated Regression (BTR)

In the literature, only two statistical regression models of the classic DEA model efficiency estimates are well-defined and significant (SIMAR; WILSON, 2011). The model proposed by Simar and Wilson (2000), Bootstrap Truncated Regression, offers a consistent estimate of the efficiency scores based on a confidence interval. The results of this regression is called the second stage of DEA model evaluation. It is worthwhile noting that Banker and Natajaran (2008) proposed another estimate based on the square minimums method. The parametric regression proposed by Simar and Wilson (2000) tests the significance of exogenous contextual variables in the efficiency scores assigned by the DEA models, using a specific confidence interval (5%). The technique consists of simulating a new sample distribution through a data generation process using the DEA scores. A new dataset is created and the scores are re-estimated using this new dataset. Repeating the process several times, the technique provides a good approximation of the true distribution of the sample (WANKE, 2012).

Cooper, Seiford and Tone (2006) noted an uptick in the number of studies blending DEA scores obtained during the first stage with those obtained during a multivariate data analysis (regression) in a second stage, when the scores are incorporated in the form of dependent variables (WANKE; BARROS, 2015b). Simar and Wilson (2000) used the following regression:

$$SE_j = a + z_j\delta + \varepsilon_j, \qquad j = 1,..., n \qquad (11)$$

In (11), SE_j is the statistical error; ε_j is the vector with the observation of DMU variables. The distribution of ε_j is restricted by condition $\varepsilon_j \geq 1 - a - z_j\delta$ (both sides of the equation (11) are limited by the unit, as SE ≤ 1) (WANKE; BARROS, 2015b). According to Simar and Wilson (2000), the distribution of ε_j is normal, truncated (on the left), with a zero mean (before being truncated), unknown variance, and truncation determined by the previous condition. It is expected that ε_j is related to the scale efficiency of the DMUs, SE_j. Reallocating, in (11), SE_j by the classic DEA model estimates, $\overline{SE}_j$, the econometric model is:

$$\overline{SE}_j \approx a + z_j\delta + \varepsilon_j, \qquad j = 1,... n \qquad (12)$$

Where

$$\varepsilon_j \sim N(0, \sigma_\varepsilon^2), \text{ whereby } \varepsilon_j \geq 1 - a - z_j\delta, \qquad j = 1,..., n \qquad (13)$$

which is estimated maximizing the corresponding likelihood function, (δ, σ^2), considering the collected database. The BTR parametric regression is used to construct a confidence interval for the parametric estimates $(\delta, \sigma_\varepsilon^2)$, which incorporates the assumed distribution and the information on the parametric structure. Further details may be found in Simar and Wilson (2000). The free version of the R 3.2.2 software was used (https://cran.r-project.org/) to calculate the efficiency scores for the classic DEA CCR and DEA BCC models, as well as the BTR models, as presented in Section 2.5 below.

2.5 DATA ANALYSIS AND DISCUSSION OF THE RESULTS

The section presents and analyzes the database and discusses the results of the classic DEA models, the SE, and the RTS types of the DMUs. Based on the BTR regression, the effects of selected contextual variables on efficiency scores are discussed. Next, a grouping of railway concessionaires in clusters is proposed and public policies are discussed for increasing the efficiency of each of them. Finally, the robustness of the results is discussed by analyzing the presence of outliers in the sample.

2.5.1 Data Analysis

The DEA CCR and DEA BCC models were calibrated as shown in Table 2.3. The wide data scatter is evident, a reflection of the different operating scales of Brazilian rail concessionaires. The selected inputs and output are those used by the industry regulator (ANTT) to control rail concessionaire performances (ANTT, 2015).

Table 2.3:
Data Statistics - Inputs and Output.

	Input 1	Input 2	Output
	wagons (in circulation)	employees (labor)	TKU million
Minimum value	64	136	153
Median	6,217	1,933.5	9,318
Mean	8,122	3,491.6	24,627
Maximum value	19,692	10,139	104,177
Standard deviation (SD)	7,132.74	3,183.87	32,951.91

DMUs = 60.

The number of DMUs should exceed the maximum value between the number of inputs times the number of outputs and triple the sum of the number of inputs plus the number of outputs (COOPER; SEIFORD; TONE, 2006). In order to confer greater discriminatory power among the efficiencies found in the DEA models, each railway-year combination was considered as one DMU for a total of 60 DMUs. This approach has been used by several researchers (BARROS; WANKE, 2015; BHANOT; SINGH, 2014; GEORGE; RANGARAJ, 2008; GUZMÁN; MONTOYA, 2011; JITSUZUMI; NAKAMURA, 2010; KABASAKAL; KUTLAR; SARIKAYA, 2013; KUTLAR; KABASAKAL; SARIKAYA, 2013; OUM; PATHOMSIRI; YOSHIDA, 2013; SHI; LIM; CHI, 2011; WANKE; BARROS, 2015a). Barros and Wanke (2015) analyzed the efficiency of African airlines from 2010-2013 and considered 116 samples formed by the combination of 29 airlines for a period of four years. Bhanot and Singh (2014) collected secondary data of three Indian Railways from 2005-2006 till 2010-2011, making a competitive comparison of the 18 DMUs. George and Rangaraj (2008) collected data for the years 1998 and 1999 with nine zones and for the years 2004 and 2005 with 16 zones and analyzed the efficiency of the zones in four models. Gúzman and Montoya (2011) assessed the efficiency of 18 Spanish rail companies of five years during the period of 1910-1922. Jitsuzumi and Nakamura (2010) analyzed the efficiency of 53 Japanese rail passenger operators from 1998-2003. Kabakasal, Kutlar and Sarikaya (2013) and Kutlar, Kabakasal and Sarikaya (2013) analyzed the efficiency of railway companies worldwide during the period of 2000-2009. Oum, Pathomsiri and Yoshida (2013) studied the efficiency levels of Japanese domestic intercity travel companies in the mainland area over 9 years. Shi, Lim and Chi (2011) studied the efficiency of seven Class I US railroads during the period of 2002-2007. Wanke and Barros (2015a) analyzed the efficiency Brazilian railways comprising ten different individuals distributed 9 years during the period of 2004-2012.

Table 2.4 presents the descriptive statistics for the selected contextual variables that will help provide insights in relation to the DMU efficiency scores. 58% of the DMUs haul cargo consisting mainly of either agricultural commodities (25%) or mineral commodities (33%). The railway network consists mainly (58% of the DMUs) of metric gauge tracks, with 25% of the DMUs operating through shared infrastructure (permanent rail) with other operators (ALL.P, FNS and EFC). These contextual variables will be used to investigate whether the predominant cargoes (mineral and non-mineral; agricultural and non-agricultural), track gauge (broad or metric) and the type of operation (shared infrastructure or monopoly) are significant for rail concessionaire performance.

Table 2.4:
Descriptive Statistics for Contextual Variables.

Contextual variables	Predominant cargo type						Gauge			Type of operation		
	(0=non-mineral 1=mineral)			(0=non-agricultural; 1=agricultural)			(0=metric; 1=broad)			(0=shared; 1=monopoly)		
median	0						0			0		
mean	0.33			0.25			0.42			0.25		
nº DMUs and frequency distribution	0 1	40 20	67% 33%	0 1	45 15	75% 25%	0 1	35 25	58% 42%	0 1	15 45	25% 75%

2.5.2 Findings and Discussion (Efficiency, SE and RTS Analysis)

The DMU efficiency scores analyzed on the basis of the classic DEA CCR and DEA BCC models are presented in Table 2.5. The models were output-driven because the grantor authority is eager for rail concessionaires to step up production along awarded segments to respond more effectively to demand. This entails answering the question, "How much proportionately can the output (TKU) of a DMU be increased without altering the amount of inputs used (wagons in circulation and employees)?” Table 5 also presents scale efficiencies (SE) and return to scales (RTS) for each DMU in the sample.

Table 2.5:
Efficiency Scores for the DEA CCR and DEA BCC Models, Scale Efficiency (SE), Sum of Weights (Σλ) and Return to Scale (RTS).

#	DMU	DEA CCR	DEA BCC	SE	Σ (λ)	RTS	#	DMU	DEA CCR	DEA BCC	SE	Σ (λ)	RTS
1	EFC.10	1.000	1.000	1.000	1.000	Constant	31	FCA.13	0.172	0.175	0.984	1.024	decreasing
2	EFC.13	1.000	1.000	1.000	1.000	Constant	32	FCA.12	0.169	0.169	1.000	0.966	increasing
3	EFC.11	0.958	1.000	0.958	1.097	decreasing	33	ALL.P.13	0.164	0.165	0.990	0.237	increasing
4	EFC.12	0.957	1.000	0.957	1.069	decreasing	34	ALL.S.13	0.163	0.163	1.000	0.958	increasing
5	EFC.14	0.944	1.000	0.944	1.212	decreasing	35	ALL.S.14	0.154	0.154	1.000	0.945	increasing
6	ALL.N.14	0.554	0.558	0.994	0.446	increasing	36	FCA.11	0.154	0.154	1.000	0.897	increasing
7	EFVM.10	0.548	0.705	0.776	1.474	decreasing	37	FCA.14	0.152	0.176	0.865	1.190	decreasing
8	EFVM.14	0.542	0.698	0.776	1.474	decreasing	38	ALL.S.11	0.152	0.174	0.871	1.182	decreasing
9	ALL.N.13	0.524	0.550	0.953	0.439	increasing	39	ALL.S.10	0.149	0.168	0.885	1.162	decreasing
10	ALL.N.12	0.515	0.544	0.948	0.415	increasing	40	ALL.O.13	0.148	0.152	0.973	0.099	increasing
11	EFVM.11	0.493	0.718	0.687	1.600	decreasing	41	ALL.O.14	0.146	0.150	0.974	0.103	increasing
12	EFVM.13	0.484	0.691	0.700	1.476	decreasing	42	ALL.P.14	0.144	0.146	0.992	0.268	increasing
13	EFVM.12	0.481	0.711	0.676	1.526	decreasing	43	ALL.S.12	0.132	0.156	0.844	1.312	decreasing
14	FNS.14	0.475	0.493	0.963	0.073	increasing	44	ALL.P.12	0.092	0.095	0.964	0.506	increasing
15	FNS.13	0.462	0.489	0.945	0.051	increasing	45	FTC.14	0.091	0.100	0.909	0.031	increasing
16	FNS.12	0.457	0.484	0.944	0.050	increasing	46	ALL.P.11	0.089	0.091	0.973	0.580	increasing
17	MRS.14	0.419	0.619	0.677	1.523	decreasing	47	FTC.13	0.081	0.090	0.902	0.029	increasing
18	FNS.11	0.414	0.679	0.610	0.046	increasing	48	ALL.O.12	0.075	0.084	0.889	0.250	increasing
19	F.OES.11	0.414	1.000	0.414	0.005	increasing	49	ALL.O.10	0.074	0.083	0.897	0.264	increasing
20	MRS.11	0.410	0.588	0.696	1.481	decreasing	50	ALL.P.10	0.070	0.072	0.978	0.628	increasing
21	MRS.10	0.405	0.552	0.735	1.404	decreasing	51	ALL.O.11	0.069	0.070	0.987	0.263	increasing
22	MRS.13	0.402	0.590	0.682	1.513	decreasing	52	FTC.12	0.067	0.075	0.898	0.028	increasing
23	MRS.12	0.401	0.599	0.670	1.539	decreasing	53	F.OES.14	0.065	0.312	0.207	0.045	increasing
24	ALL.N.11	0.389	0.407	0.955	0.453	increasing	54	FTC.10	0.064	0.071	0.901	0.029	increasing
25	FNS.10	0.369	0.659	0.560	0.042	increasing	55	FTC.11	0.059	0.066	0.901	0.029	increasing
26	F.OES.10	0.368	0.611	0.602	0.007	increasing	56	FTL.12	0.049	0.050	0.982	0.141	increasing
27	ALL.N.10	0.343	0.345	0.994	0.428	increasing	57	FTL.11	0.044	0.045	0.984	0.152	increasing

Table 2.5: Continued.

#	DMU	DEA CCR	DEA BCC	SE	Σ (λ)	RTS	#	DMU	DEA CCR	DEA BCC	SE	Σ (λ)	RTS
28	F.OES.13	0.266	0.546	0.486	0.006	increasing	58	FTL.14	0.042	0.043	0.982	0.142	increasing
29	F.OES.12	0.259	0.433	0.597	0.007	increasing	59	FTL.10	0.041	0.042	0.986	0.176	increasing
30	FCA.10	0.173	0.173	1.000	0.876	increasing	60	FTL.13	0.037	0.037	0.982	0.144	increasing

Table 2.6 presents the descriptive statistics for the results obtained through the DEA CCR and DEA BCC models and the SE. There is considerable asymmetry among the rail concessionaires, as indicated by the gap between the minimum (0.037) and maximum (1.000) efficiency in the DEA CCR model, with constant returns of scale. The mean overall technical efficiency is low (0.309) for the DMU group analyzed. This suggests a mean overall inefficiency of 69.1% for the system, indicating that rail concessionaires must be encouraged to step up production (TKU million) in order to operate at the efficiency frontier. Also notable is the fact that the mean efficiency found in the DEA BCC model (0.383), with variable returns to scale, reflects a mean management inefficiency of 61.7% for production management, based on the inputs used. This management inefficiency outstrips the mean inefficiency found in the operations scale (14%). The results suggest that, on average, management inefficiency is more important than DMU scale inefficiency when we try to explain the mean overall technical inefficiency found in the DEA CCR model (69.1%). Below, we will analyze the cases (DMUs) in which scale inefficiency, instead, is greater than management inefficiency.

Table 2.6:
Descriptive Statistics of the DEA CCR and DEA BCC scores and the SE.

Statistics	DEA CRS	DEA BCC	SE
Mean efficiency	0.309	0.383	0.860
Minimum	0.037	0.037	0.207
Quartile 1	0.091	0.099	0.766
Mean	0.173	0.244	0.945
Quartile 3	0.458	0.602	0.983
Maximum	1.000	1.000	1.000
% Mean Inefficiency	69.1	61.7	14.0

Figure 1 represents the 11 DMUs with SE lower than the pure technical efficiency found in the DEA BCC model, which are located above the diagonal line in the graph. This result underscores the conclusion that management inefficiency is more widespread than scale inefficiency in DMUs operations when attempting to explain the overall technical efficiency of the DMUs in the sample (47 DMUs located below the diagonal line in the graph).

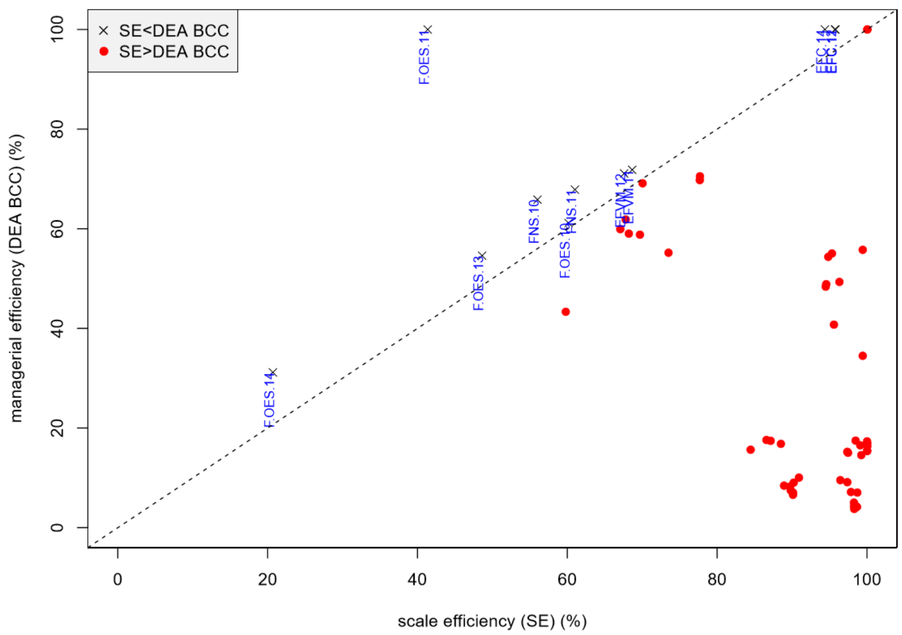

Figure 2.1: Pure Technical Efficiency (%) x Scale Efficiency (%)

Only 3.3% of the DMUs (two DMUs) were located on the efficiency frontier of the DEA CCR model, i.e., concessionaire EFC, for years 2010 and 2013. The performances in these years are benchmarks for the other DMUs (rated as inefficient) and represent the best practices in the sample. Concessionaire EFC specializes in the transport of mineral commodities (ores), mainly in the North Region, on broad gauge and with shared infrastructure from Açailândia to Itaqui Port, both in Maranhão State, where it receives trains of the FNS or VALEC (VLI) concessionaires. The efficiency frontier in the DEA BCC model, represented by convex linear combinations of the production possibilities set, with variable returns of scale, consists of 10% of the DMUs in the sample (six DMUs). Two DMUs garnered an efficiency score equal to one in the DEA CCR model, thus operating with an SE rated as optimum, and four DMUs were ranked as efficient in the DEA BCC model (albeit inefficient in the DEA CCR model) with sub-optimum SE (concessionaires EFC and F.OES). The EFC concessionaire presented an SE that is very close to the scale efficiency rated as optimum in 2011, 2012 and 2014 (0.958, 0.957 and 0.944, respectively) and had outputs among the highest in the sample (99,567, 103,399 and 104,177 TKU million, respectively). In contrast, concessionaire F.OES presented the lowest SE but one in the sample (0.414) and a very low output (209 TKU million, the sixth lowest in the sample). These results undermine the unfeasibility of this side of the efficiency frontier. Despite proportionally efficient output compared to low input levels, this DMU (F.OES) cannot be taken as a benchmark for other inefficient DMUs, due to the low output. Concessionaire F.OES is a monopoly carrying agricultural commodities on metric gauge track in Southern Brazil.

Table 2.7 separates the inefficient concessionaires in quartiles, as proposed by Kumar and Gulati (2008). This is the first step in grouping the concessionaires by similar performance, which will be presented in more detail in 5.4. The quartiles are classified as “Most Inefficient” (Category 1); “Below Mean Efficiency” (Category 2); “Above Mean Efficiency” (Category 3); and “Marginally Inefficient” (Category 4). The DEA CCR model scores were used here as they are more restrictive than those of the DEA BCC model and generally do not exceed the scores found in the DEA BCC model (COOPER; SEIFORD; TONE, 2006).

Table 2.7:
Ranking of Inefficient Rail Concessionaires per the DEA CCR Model – RTS in brackets.

Category 1 (Most Inefficient)	Category 2 (Below Mean Efficiency)	Category 3 (Above Mean Efficiency)	Category 4 (Marginally Inefficient)
ALL.O.10 (i)	ALL.S.10 (d)	ALL.N.10 (i)	EFVM.10 (d)
ALL.P.10 (i)	FCA.10 (i)	**F.OES.10 (i)**	**EFC.11 (d)**
FTC.10 (i)	ALL.S.11 (d)	**FNS.10 (i)**	**EFVM.11 (d)**
FTL.10 (i)	FCA.11 (i)	MRS.10 (d)	ALL.N.12 (i)
ALL.O.11 (i)	ALL.P.12 (i)	ALL.N.11 (i)	**EFC.12 (d)**
ALL.P.11 (i)	ALL.S.12 (d)	**F.OES.11 (i)**	**EFVM.12 (d)**
FTC.11 (i)	F.OES.12 (i)	**FNS.11 (i)**	ALL.N.13 (i)
FTL.11 (i)	FCA.12 (i)	MRS.11 (d)	EFVM.13 (d)
ALL.O.12 (i)	ALL.O.13 (i)	FNS.12 (i)	FNS.13 (i)
FTC.12 (i)	ALL.P.13 (i)	MRS.12 (d)	ALL.N.14 (i)
FTL.12 (i)	ALL.S.13 (i)	MRS.13 (d)	**EFC.14 (d)**
FTC.13 (i)	**F.OES.13 (i)**	MRS.14 (d)	EFVM.14 (d)
FTL.13 (i)	FCA.13 (d)		FNS.14 (i)
F.OES.14 (i)	ALL.O.14 (i)		
FTL.14 (i)	ALL.P.14 (i)		
	ALL.S.14 (i)		
	FCA.14 (d)		
	FTC.14 (i)		
15 DMUs (25%)	18 DMUs (30%)	12 DMUs (20%)	13 DMUs (22%)
67% assorted cargo; 100% metric gauge; 87% monopoly;	83% assorted cargo; 100% metric gauge; 83% monopoly;	100% commodities; 83% broad gauge; 75% monopoly;	100% commodities; 100% broad gauge; 62% monopoly;

Table 2.7: Continued.

100% increasing RTS; 100% SE>DEA BCC	72% increasing RTS; 94% SE>DEA BCC	58% increasing RTS; 67% SE>DEA BCC	62% decreasing RTS; 62% SE>DEA BCC

(i) =increasing RTS; (d) = decreasing RTS; boldface: DMUS with scale efficiency (SE) < DEA BCC model efficiency.

In Table 7 we see that forty inefficient DMUs (67% of the DMUs) presented increasing RTS (IRS) and were located in Categories 1, 2, 3 and 4, while eighteen inefficient DMUs (30% of the DMUs) presented decreasing RTS (DRS) and were located in Categories 12, 3 and 4. The classification of DMUs, however, does not yet exhibit the desired power of discrimination. Item 5.4, following, presents the concessionaire clusters which the increasingly efficiency-driven public police are based on.

2.5.3 Significance of Contextual Variables on DMU's Efficiency

The rDEA package (R software, version 3.2.2) allows contextual variable significance to be calculated, using the Bootstrapped Truncated Regression model. The selected contextual variables are type of cargo (mineral commodities, yes or no; and agricultural commodities, yes or no), the network gauge (broad or metric) and the type of operation (shared infrastructure or monopoly). Tables 2.8 and 2.9 present the significance and the regression coefficients for the contextual variables, considering a 5% confidence interval.

Table 2.8:
Coefficients and confidence interval (5%) of the Bootstrap Truncated Regression - constant returns to scale.

Coefficients	Value	Lower limit (2.5%)	Upper limit (97.5%)	
(Intercept)	11.04359	0.5217575	17.076070	*
Mineral commodities (yes=1)	-24.83153	-44.9627981	-4.150561	*
Agricultural commodities (yes=1)	-27.58362	-80.0324654	-7.144247	*
Gauge (broad=1)	-42.37638	-78.5104217	-18.235067	*
Type of regulation (shared=1)	23.79311	-4.1079117	53.076270	

* significant.

Considering constant returns to scale, the BTR results show that, in the sample used, the predominant commodity (mineral or agricultural) transport and broad gauge networks were significant in DMU efficiency scores. The type of operation (shared infrastructure) variable was not significant to explain DMU efficiency within the confidence interval used. These results corroborate the findings of the DEA CCR model, where efficient and marginally efficient

DMUs (Category 4) have the predominant characteristic of carrying agricultural and mineral commodities (100%) and operating on broad gauge tracks (100%).

Table 2.9:
Coefficients and confidence interval (5%) of the Bootstrap Truncated Regression - variable returns to scale.

Coefficients	Value	Lower limit (2.5%)	Upper limit (97.5%)	
(Intercept)	11.30441	-0.7180416	16.821980	
Mineral commodities (yes=1)	-24.74809	-57.0755549	-9.418462	*
Agricultural commodities (yes=1)	-81.89649	-173.8884773	-31.225447	*
gauge (broad=1)	-40.40423	-76.1321382	-13.026818	*
Type of regulation (shared=1)	27.49152	-1.1888998	60.158997	

* significant.

Considering variable returns to scale, the BTR results show that, in the sample used, the mode of transport of the predominant commodity (mineral or agricultural) was also significant, as was broad gauge networks in DMU efficiency scores. The type of operation (shared infrastructure) variable was not significant to explain DMU efficiency in the confidence interval used. These results corroborate the findings of the DEA BCC model, where efficient DMUs have the predominant characteristic of carrying all commodities and operating on broad gauge tracks. Agricultural and mineral cargoes are well suited to rail freight and can be carried in large volumes on long trains, ensuring better use of inputs, economies of scale and lower operating costs. The results suggest the importance of economies of scale for the efficiency of operations.

Operating with shared infrastructure did not appear as a significant variable for operator efficiency scores, despite regulatory incentives. This suggests that transport operations on more competitive structures, with more than one operator, did not influence DMU performance in the sample analyzed. The predominant cargo type and rail gauge proved more relevant than the market structure of the operations. Bearing in mind the sample used, operations on shared permanent rail were not confirmed as an element enhancing operator efficiency. It still remains to be discovered whether monopoly operations (single permanent rail operator) are significant for DMU efficiency. Further studies must be conducted in order to assess the significance of monopolistic operations including new variables in the DEA models, for example, which could encompass gains in scale for operating costs or the tariff/km prices of shared and monopolist operations (undesirable output).

2.5.4 Public Policies

Figure 2 clusters the rail concessionaires with similar characteristics through the joint analysis of the efficiency of the BTR results and RTS of the DMUs of the sample. Plotted points refers to the efficiency scores in BTR crs model (y axis) and the RTS type of each DMU (x axis), whether IRS (black), CRS (red) and DRS (blue). Groups are clustered considering the value of the efficiency scores, whether above or below mean, and the RTS type. The benchmark concessionaire for the other inefficient DMU is EFC (Group E). It is worth noting that the option for the BTR efficiency scores relates to robustness, despite the fact that the results obtained with the DEA CCR model and BTR crs model do not alter the composition of the clusters proposed below.

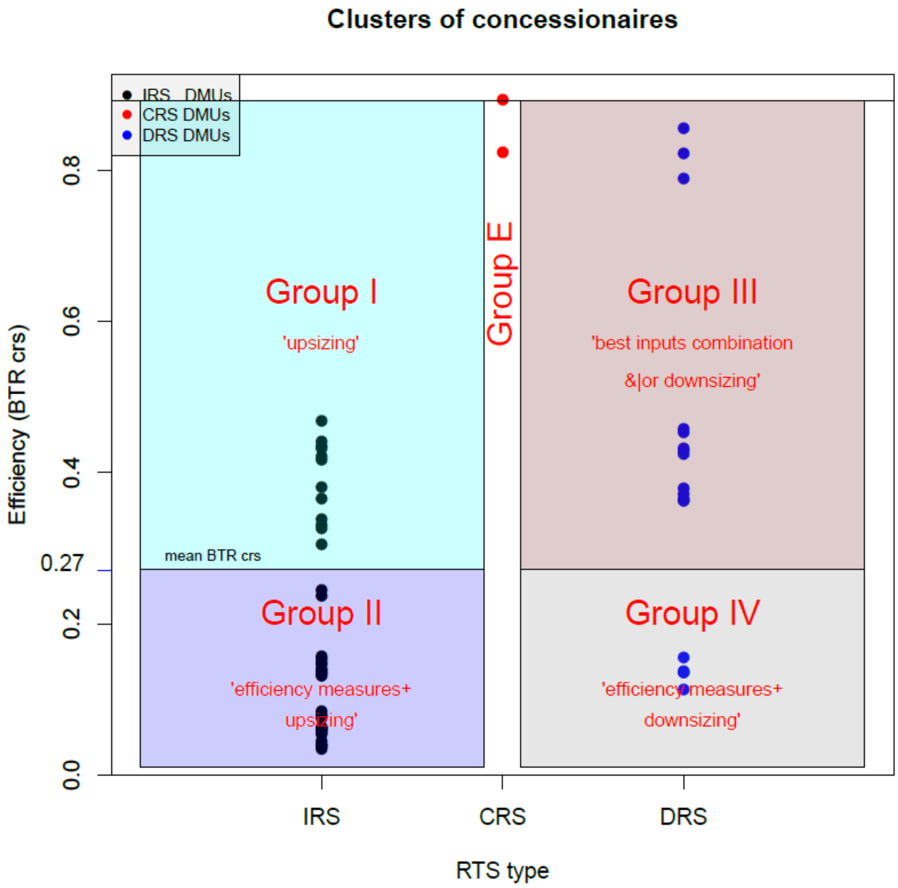

Figure 2.2: Efficiency x RTS type and similar concessionaire groups (clusters)

Table 2.10 presents the proposed clustering characteristics of the rail concessionaires. Eight in twelve concessionaires (83%) remained in the same cluster throughout the five years of the sample (ALL.N, FNS, ALL.O, ALL.P, FTC and FTL, EFVM and MRS), indicating the robustness of the grouping. The other concessionaires (17% – F.OES, ALL.S, FCA and EFC) migrated from one cluster to another between 2010 and 2014 due to input and output variations.

The mean transport distance (MTD) presented in Table 10 is the ratio between the TKU million variable (output) and the annual tonnage transported (TU) by each DMU in the group.

Table 2.10:
Characteristics of DMUs grouped into clusters by Efficiency, SE and RTS.

Groups (clusters)		Characteristics			Other characteristics			Concessionaires/ DMUs
		Mean score (eff) (CCR) (BTR)	SE mean	RTS	Cargo Type	MTD (km)	Gauge	
I	Upsizing	mean efficiency≤ eff <1.0 (0.44) (0.39)	<1.0	IRS	100% commodities	1.007.0	83% broad	**ALL.N, FNS,** F.OES (10, 11)
II	efficiency measures +upsizing	0< eff <mean efficiency (0.11) (0,10)	<1.0	IRS	71% assorted cargo	472.6	82% metric	**ALL.O, ALL.P, FTC, FTL, F.OES** (12-14), **ALL.S** (13-14), FCA (10-12)
III	best inputs combination and/or downsizing	mean efficiency≤ eff <1.0 (0.57) (0.49)	<1.0	DRS	100% commodities	600.0	62% broad	**EFVM, MRS,** EFC (11-12, 14)
IV	efficiency measures +downsizing	0< eff <mean efficiency (0.15) (0.13)	<1.0	DRS	100% assorted	700.8	100% metric	**FCA** (13-14), ALL.S (10-12)
E	Efficient	(1.0) (0.85)	=1.0	CRS	100% commodities	873.0	100% broad	**EFC** (10, 13)

Boldface: typical concessionaires in their groups.
Concessionaires/DMUs: when year is not mentioned, refers to all years (10-14).
Mean eff DEA CCR = 0.31; mean eff BTR (crs) = 0.27.

Findings suggest that the grantor authority should adopt a specific set of objectives for each of the efficiency clusters that groups rail concessionaires with similar performance in terms of overall technical efficiency, BTR scores, scale efficiency (SE) and returns to scale (RTS). These objectives are presented below. Group I ("upsizing"), characterized by efficiency above the mean and IRS, has a greater need for increased inputs (wagons and labor) and other operating assets (such as terminals and rail access) in order to expand the scope of their activities. Group II ("efficiency measures+upsizing"), characterized by efficiency below mean and IRS, requires, together, improvement of management practices (production management) and tracking of infrastructure upgrades (to boost assets turnover) in addition to expanding new inputs and operating assets. Stand-alone measures will not be able to offset the various sources of inefficiency. Group III ("combination of best inputs and/or downsizing"), characterized by efficiency above mean and DRS, requires firm steps to reduce inputs and/or ensure a more even balance in their combination (for the more efficient members of the Group). Group IV ("efficiency measures+downsizing"), characterized by efficiency below the mean and DRS, requires joint steps to attain better management practices, track infrastructure upgrades and lower inputs. Group E ("efficient") consisted of a single concessionaire that is the benchmark for others, is less dependent on incentives in terms of the scale of its activities, better management practices or tracking of infrastructure upgrades. Discussion of incentives to continue activities at a rate commensurate with rising demand still remains. Rail sector financing mechanisms may tailor their financial support policies to each of the proposed groups in order to enhance concessionaire efficiency, while also pursuing greater efficiency in the allocation of their proper resources. For instance, special financial conditions for upsizing (Group I) and for improvements in management and infrastructure (Groups II and IV).

The results of the influence of the contextual variables on DMU efficiency indicate that it is important to emphasize the feasibility of the conditions needed for operators to handle the transport of agricultural and mineral commodities on broad gauge systems, which are characteristic of the rail corridors in North and Center-West Brazil. However, mechanisms for increased competition in the rail network have not yet resulted in enhanced efficiency among DMUs operating shared tracks. The conclusions suggest that DMUs on Groups II and IV, with efficiency below the mean and carrying mainly assorted cargo on metric gauge tracks, are the ones most exposed to regulatory competitive pressures and the arrival of more efficient new operators.

2.5.5 Analysis of Outliers

Outliers are firms that differ from others in terms of the set of production possibilities for some specific reason and can have a significant impact on DEA models (BOGETOFT; OTTO, 2011). The presence of outliers has been a concern in the DEA literature over the past three decades due to the limitations of classic models, since there has been no clear definition as to how to identify outliers in DEA models (KHEZRIMOTLAGH, 2013). One possible indicator of the presence of an outlier (or group of outliers) is a sharp drop in efficiency scores obtained from selected DMUs (BOGETOFT; OTTO, 2011). Part of this problem may derive from the presence of slacks, with efficiency scores not taken into account in classic DEA models. Bogetoft and Otto (2011) provide some reasons for the presence of outliers: (a) error in the database; (b) correct, albeit atypical observations (high leverage points); and (c) observations that suggest low or high performance in efficiency scores. In addition, Khezrimotlagh (2013) points to the following as causes of outliers: (a) the presence on non-homogeneous DMU among observations; and (b) the presence of “Near and Far Data”, 'when one DMU uses a much greater (bit less) value of input and only produces a bit greater (much less) value of output’. As a precautionary measure, extreme observations, that are hard to replicate, can be classified as outliers. However, parsimony should be considered in the treatment of outliers, since these extreme observations can also represent the best adopted business practices or new technological practices used that expand the efficiency frontier, making the DMU(s) a reference for the others.

2.5.5.1 Identification of Outliers

Figure 2.3 below shows the scatterplot of the variables considered in the efficiency evaluation of Brazilian railway sector concessionaires according to Table 3. The most productive DMU (TKU million) are possible outlier candidates (EFC in all the years considered in the sample), as suggested by the TKU million x wagons graph. The boxplot in Figure 4 reinforces this possibility, since it indicates the highest values as outliers (as attained by concessionaire EFC).

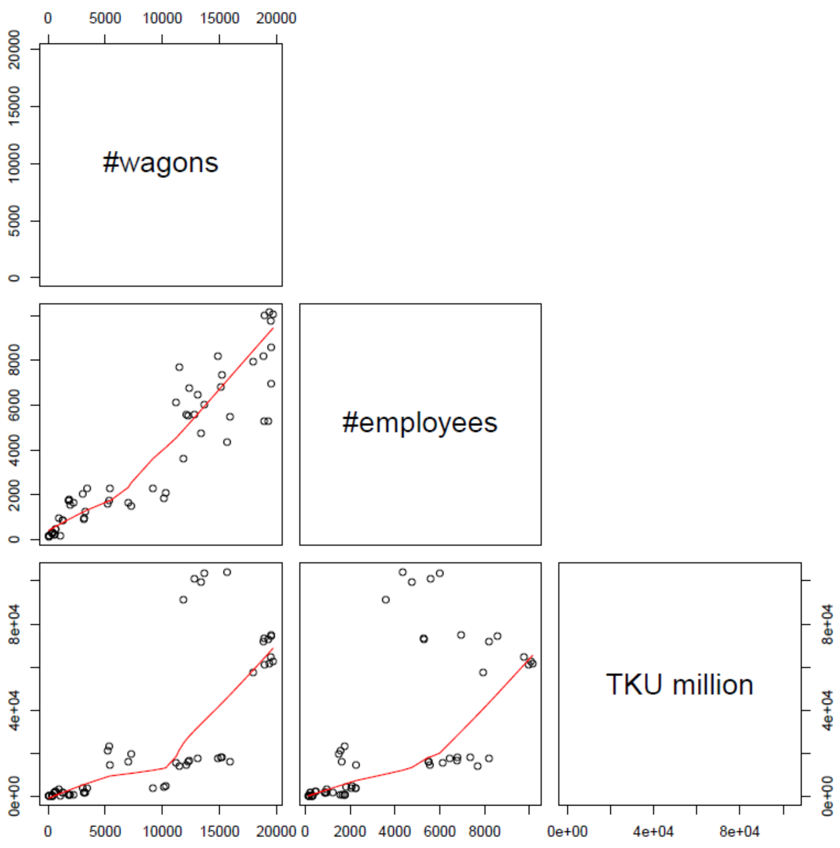

Figure 2.3: Scatterplot of the variables used in the DEA modeling

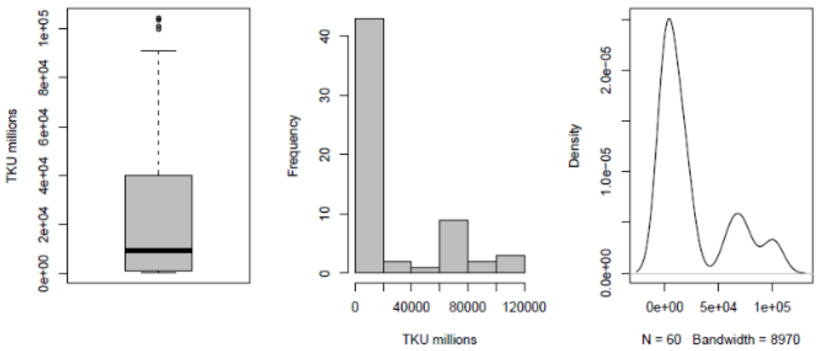

Figure 2.4: Box plot, histogram and density plot of output (TKU million)

2.5.5.2 Impact on the DEA Models, BTR Regression and Composition of Clusters

Figure 2.5 below shows the density of the efficiency results of the DMUs in the various models used, considering the sample both with and without the outliers. Note that the curves obtained without outliers, in red, are smoothed in all models analyzed. There is greater uniformity of results when outliers are removed.

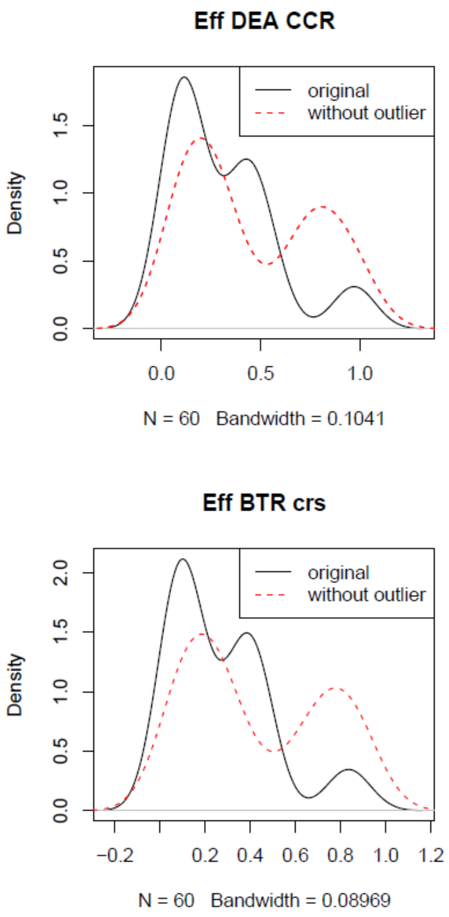

Figure 2.5: Comparison of the efficiency results obtained in classical DEA models (CCR, BCC) and in BTR regressions (crs and vrs), with and without outliers

The results of the BTR using the sample without outliers are shown in Tables 2.11 and 2.12 below. In the model considering constant returns to scale, the only change with respect to the results shown in Table 8 above is the significance of the contextual variable shared operation, but in the direction opposite to efficiency. The estimators of the contextual variables mineral commodities and agricultural commodities remain significant, however at a lower magnitude than the estimators in Table 2.8 above, due to the removal of outliers. The estimator of the variable broad gauge remains significant and with greater magnitude than in Table 2.8.

Table 2.11:
Coefficients and confidence interval (5%) of the Bootstrap Truncated Regression - constant returns to scale, without outliers.

Coefficients	Value	Lower limit (2.5%)	Upper limit (97.5%)	
(Intercept)	5.026035	1.030678	7.6367598	*
Mineral commodities (yes=1)	-5.780596	-13.739965	-0.4649022	*
Agricultural commodities (yes=1)	-20.775154	-48.359169	-9.2483970	*
Gauge (broad=1)	-56.996579	-86.483112	-33.4670312	*
Type of regulation (shared=1)	52.214980	28.817772	82.3479973	*

* significant.

The same is true in the BTR model with variable returns to scale. The estimator of variable shared operation was significant, in the direction opposite to efficiency. The estimators of the contextual variables mineral commodities and agricultural commodities remain significant, albeit at lower magnitude than the estimators in Table 2.9 above, due to the exclusion of outliers. The estimator of the variable broad gauge remains significant and with greater magnitude.

Table 2.12:
Coefficients and confidence interval (5%) of the Bootstrap Truncated Regression - variable returns to scale, without outliers.

Coefficients	Value	Lower limit (2.5%)	Upper limit (97.5%)	
(Intercept)	5.351000	1.692594	7.8427679	*
Mineral commodities (yes=1)	-5.538226	-12.834495	-0.3317294	*
Agricultural commodities (yes=1)	-49.233458	-98.657984	-22.5447583	*
gauge (broad=1)	-48.154161	-89.770995	-22.3049051	*
Type of regulation (shared=1)	45.455520	19.426970	85.7702325	*

* significant.

Table 2.13 below shows the set of companies belonging to each of the proposed clusters, both including and excluding outliers. Of note is the improvement of the DMU ALL.N over the years until reaching the frontier in 2014 (predominantly agricultural commodities cargo, broad gauge and monopolistic operation) along with the DMU EFVM.10 (predominantly mineral commodities cargo, metric gauge and monopolistic operation). The migration of DMU ALL.S in years 2013 and 2014 from Group II to Group IV reinforces the need to cut inputs and make improvements in administration and infrastructure. The other DMUs remain ultimately in the same clusters of the analysis with outliers.

Table 2.13:
Clusters composition, with and without outliers.

Groups (*clusters*)		Concessionaires/ DMUs With outliers	Concessionaires/ DMUs Without outliers
I	*Upsizing*	**ALL.N, FNS,** F.OES (10, 11)	**ALL.N** (11-13), **FNS, F.OES** (10-13)
II	*efficiency measures + upsizing*	**ALL.O, ALL.P, FTC, FTL, F.OES** (12-14), **ALL.S** (13-14), FCA (10-12)	**ALL.O, ALL.P, FTC, FTL,** F.OES (14)
III	*best inputs combination and/or downsizing*	**EFVM, MRS,** EFC (11-12, 14)	**EFVM** (11, 14), **MRS,** ALL.N(10)
IV	*efficiency measures + downsizing*	**FCA** (13-14), ALL.S (10-12)	**FCA**, **ALL.S**
E	*Efficient*	**EFC** (10, 13)	EFVM (10), ALL N (14)

Boldface: typical concessionaires in their groups.
Concessionaires/DMUs: when year is not mentioned, refers all years (10-14).
In red: DMUs that have changed position, considering sample without outliers.
Mean eff DEA CCR = 0.46; mean eff BTR (crs) = 0.43 (without outliers).

In the present case, the importance of the outliers in the benchmarking analysis is recognized. The DMU EFC is controlled by the Vale mining company. Vale operates a rail corridor that is part of a logistics chain for exporting mineral commodities in a competitive market. The efficiency of this logistics chain is critical to Vale maintaining competitive export capacity. For this purpose, the company uses both operational and technological techniques to obtain superior results, including long compositions (300 wagons), automatic discharge wagons (to reduce the transit time of the compositions in cargo loading and unloading), eliminating railroad crossings (for greater freight speed), high power AC locomotives (for greater traction), as well as favorable locational factors of the rail (favorable longitudinal topography of permanent rail). Maintaining the EFC in the entire DMU sample set is important, precisely to expand the efficiency frontier through operational and technological practices of reference for the other DMUs.

2.6 CONCLUSIONS

The mean efficiency of Brazilian rail concessionaires as a group is low, not exceeding 38.3%. It may be inferred that the Brazilian rail system generally operates with an excess of inputs (wagons in circulation and labor) and/or low output (TKU million). This suggests that the mean inefficiency of the system is 61.7%. Therefore, concessionaires can boost production (TKU million), without increasing inputs, to attain frontier efficiency for their operations. To some extent, these findings are not surprising, in view of the criticism of efficiency of Brazil's rail concessionaires as a group (described in this paper). Although not homogeneous in terms of the scope of their activities (inputs) and performance, most of these companies operate with low overall technical efficiency, far from the efficiency frontier. This calls for management actions by the grantor authority to implement regulatory measures to enhance firm performance. Another noteworthy aspect is that the mean management inefficiency (61.7%) measured using the DEA BCC model is higher than the mean inefficiency found in SE of the operations (14%).

Analyzed in a second stage via BTR methodology, the effects of the contextual variables on DMU performance lead to the conclusion that transporting predominantly agricultural and mineral commodities on broad gauge tracks are significant variables in DMU efficiency scores, considering constant and variable returns to scale. Operations on shared infrastructure, with more than one operator, did not prove significant for DMU efficiency, despite recent regulatory incentives. The findings also suggest that it is important to ensure the feasibility of conditions required for concessionaires to handle shipments of agricultural and mineral commodities on broad gauge systems, which are characteristic of rail corridors in North and Center-West Brazil.

Public policies designed to enhance efficiency must address clusters of concessionaires with similar performance, promoting regulatory incentives and offering different types of financing. Group I ("upsizing") has the greatest need for measures for expanding activities (more inputs and operating assets). Group II ("efficiency measures + upsizing") requires improved management practices for production control, infrastructure upgrades (faster asset turnover) and expansion of operations. Group III ("best inputs combination and/or downsizing") requires fewer inputs and a better balanced combination (for the most efficient in this Group) while maintaining output. Group IV ("efficiency measures + downsizing") requires better management practices, infrastructure upgrades, and incentives to reduce inputs. Finally, Group E ("efficient") consists of only a single concessionaire (EFC), a benchmark for the others, that requires fewer regulatory and financing (interest rate) incentives, and more support for maintaining efficiency conditions attuned to rising demands. The conclusions also suggest that the concessionaires in Groups II and IV, characterized by efficiency below the mean and predominantly hauling assorted cargo on metric gauge tracks, are the ones most exposed to regulatory competitive pressures and the arrival of more efficient new operators. The conclusions were supported by a robustness analysis of the effects of outliers in the benchmarking analysis.

This survey focused on solving a practical problem in the Brazilian economy: exploring the conditions to enhance rail freight efficiency, paving the way for better integration of rail in the supply chain of a wide range of products. In addition to addressing the theoretical gap, these conclusions could also contribute to the formulation of cluster-specific public policies designed to boost efficiency in Brazil's rail freight sector. This survey was limited to the data available in the ANTT database. However, further studies are required, for example, comparing the performance of Brazilian rail concessionaires with operators elsewhere in the world, by extending the database. The significance of other contextual variables on concessionaire performance is also relevant. An analysis must be made of efficiency along critical segments of DMUs where demands are reaching track capacity, in order to discover which sub-segments are the most efficient and which require increased capacity and further investments. All of these studies can offer important contributions to the development of the rail freight sector in Brazil.

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3 2ND PAPER: "EFFICIENCY IN RAIL TRANSPORT: EVALUATION OF THE MAIN DRIVERS THROUGH META-ANALYSIS WITH RESAMPLING"

“EFFICIENCY IN RAIL TRANSPORT: EVALUATION OF THE MAIN DRIVERS THROUGH META-ANALYSIS WITH RESAMPLING”

Abstract

Meta-analysis is a statistical method used to make a systematic review of the literature to integrate the results of a series of studies. It is increasingly adopted in social sciences but according to our best knowledge used for the first time to aggregate and contrast findings on rail transport efficiency. The experiment adopted a permutation test to evaluate the influence of variables discussed in the literature in the mean efficiency scores. The results suggest that railways located in Japan and in the US have characteristics that push them toward increasing efficiency. The passenger rail systems reached significantly higher estimates than conventional cargo systems. Estimates from parametric and nonparametric models showed significant difference, while from nonparametric models including Data Envelopment Analysis (DEA) and from Network DEA did not. The number of variables and the ratio between the number of decision making units and the number of variables employed significantly influenced the scores. Unexpectedly, different data structures did not. Validation methods are presented. Public policies based on the empirical results are commented.

Keywords: Efficiency; rail systems; railways; meta-analysis; permutation test.

3.1 INTRODUCTION

The industrial revolution brought profound changes in transport systems. The steam engine (1765) introduced the rail system (RODRIGUE; COMTOIS; SLACK, 2013). The steam technology was commercially adopted for the transportation of coal between Manchester and Liverpool (1830). Railroads were then built in England, Western Europe, and North America. In the late 19th century, 130,000 km of railways were laid in the United States. Its rapid development can be confused with the country itself. Transcontinental railway lines were built: New York to San Francisco (1869), Trans-Canadian Railway (1886), and Trans-Siberian Railway (1904). The first railway built in Japan dates to 1872. With the improvement of the engines, the railways developed worldwide during the 20th century. Cities sprung up along the railways. Rail services became specialized. The growth of the urban population led to the construction of subway systems. However, the development of highways reduced the relative importance of the conventional rail system. The more intense use of the automobile in the cities and the urban sprawl (HARRISON, C. AND DONNELLY, 2011) brought unsustainable economic, social, and environmental costs. But the high-speed rail (HSR) technology in the sixties reinvented rail transport. Its first appearance was in Japan (Shinkansen) from Tokyo to Osaka (1964). Later in France *(Train à Grande Vitesse* – TGV) from Paris to Lyons (1981), and later in several other European countries, fully compatible with existing railways (RODRIGUE; COMTOIS; SLACK, 2013; UIC, [s.d.]). The value of new economic factors also favoured railway transport: restriction of the use of fossil fuels and of the emission of greenhouse gases (GHG), cost reduction initiatives, improved quality of life in an urban environment, and intermodalism (RODRIGUE; COMTOIS; SLACK, 2013).

The expansion of railroads reached its height in the 20th century but remains in expansion. Almost 29% of the world's railway network is installed in Europe and is dedicated to passenger transportation, due to policies of continent integration and reduction of GHG emissions, and freight transportation, resulting from polices to encourage competition (WHEAT; NASH, 2006). It handles 16% of the global passenger demand, notably in France, Germany, and UK, and 6% of the global freight demand, especially in Ukraine and Germany. Twenty-six percent is located in Asia and Oceania where the greatest productivity is observed (in the railway sector, the average traffic intensity of the railway track is commonly used as a measure of the railway's productivity and is represented by the relation of the traffic intensity [in million passenger.km] per the railway length [in km]). It handles 77% of the passenger demand, influenced by the Indian, Chinese, and Japanese markets, and 35% of freight demand, mainly in China and India. Thirty percent is found in Brazilian, Canadian, and North-American networks, and is focused almost exclusively for carrying cargo. It represents 32% of the global freight transport but only 1% of the passenger market-share. The US is recognized for operating over long average transport distance of freight (ATDF). In the railway sector, ATDF is commonly used as a measure of the mean distance travelled by cargo and is represented by traffic intensity [ton.km] per the quantity of cargo carried [ton]. The HSR technology is present mainly in Asia (75%) and in Europe (24%). The HSR traffic intensity is remarkable in Asia, especially in China and Japan, then in Europe, especially in France and in Germany. The highest productivity level is found in Japan, then the Taipei-Kaohsiung line, South Korea, France, and next Germany. Figure 3.1 summarizes the characteristics and performance indicators of the railways. Data from International Union of Railways (UIC). Created in 1922, UIC is a worldwide organisation to promote rail transport. Appendix A presents the data.

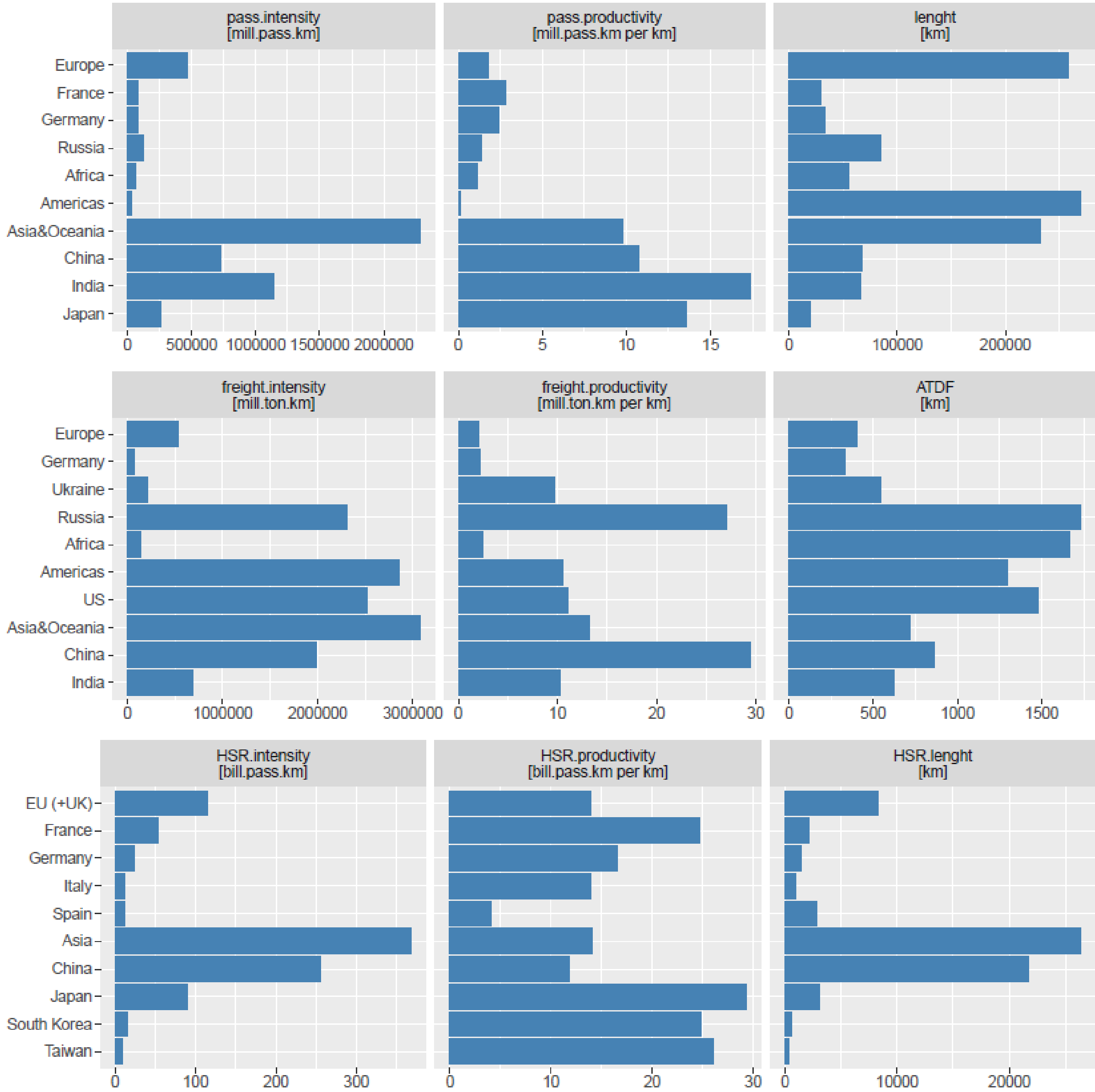

Figure 3.1: Railways and HSR technology indicators

Sources: UIC (s.d, 2015), complemented by the authors. Units in brackets. Americas: Brazil, Canada, and US.

There have been several studies in literature involving the efficiency frontier analysis of the railway transport systems of cargo and passengers between 2000 and 2016. They are shown in subsection 2. Although studies with meta-regression have already evaluated the effect of different variables on the technical efficiency (BRONS et al., 2005; KABASAKAL; KUTLAR; SARIKAYA, 2013; ODECK; BRÅTHEN, 2012; THIAM; BRAVO-URETA; RIVAS, 2001), to our best knowledge it is the first time meta-analysis is used to aggregate and contrast the results of studies on efficiency frontier of railways in its most different methods and characteristics. It was done an evaluation of the heterogeneity of the efficiency scores and possible explanations for the variance found. In search of robustness, a permutation test was used to overcome the requirement of normal distribution of the dependent variable (VIECHTBAUER, 2010) and other potential resources of misleading results in meta-analyses when in the presence of heterogeneity, few number of studies or covariates (HIGGINS; THOMPSON, 2004). The way the meta-analysis was conducted was then different than solely analysing the results of a meta-regression. The objective of this research is, using a meta-analysis of 50 observations contained in 21 selected studies on efficiency frontier of railways, carried out between 2000 and 2016, to recognize the key aspects that may influence the variation in the sample's mean efficiency that is not identified in each individual research. The main questions that this paper seeks to clarify are: "Does the geographic location of the railways influence mean efficiency estimates?", "Does the type of rail services affect the mean efficiency estimates?", "Can different methodologies applied influence mean efficiency scores?", "Can the modelling characteristics employed in each study, such as the number of variables (NVAR) or the ratio between the number of decision making units (NDMUs) and the NVAR, influence mean efficiency scores?", and "Can the database structure applied, such as panel data or cross-section, influence mean efficiency scores?" The findings contribute to the debate of which conditions (operational, location, modelling) lead to higher efficiency, which is of interest to railway managers and public agencies that control and regulate railway systems.

This paper is organized as follows. Section 3.2 contains the literature review and indicates the gap found. The characteristics and limitations of the methods used in the efficiency frontier studies are summarized. Section 3.3 describes the methodology used to analyse the data. Section 3.4 presents the database, the model adjustment, and the empirical results. Validation methods and public policies based on the findings are commented. Section 3.5 concludes the discussion showing the study's limitations and gives suggestions for further projects for advancing the knowledge of efficiency frontiers in the railway sector.

3.2 LITERATURE REVIEW

There are several studies in the literature that evaluated the efficiency frontier of the passenger and cargo rail transport systems, including efficiency rankings. Putting a focus on the methodologies applied, Bil (2013), Hilmola (2007), Bhanot and Singh (2014), and Jitsuzumi and Nakamura (2010) used the classical methodology DEA. Bil (2013) also evaluated the over-estimation of the efficiency scores by comparing the DEA classic model scores with those of the Pareto-Koopmans efficiency frontier using the SBM methodology and the assurance region method of 23 European railroads. He concluded that the results are sensitive to the models used, but probably do not have a greater impact on the efficiency ranking. Hilmola (2007) evaluated the efficiency of European railways and the adaptation of the firms at the declining of the demand and concluded that the railways in the Baltic countries, Estonia and Latvia, are the most efficient in cargo transportation. Bhanot and Sigh (2014) presented the performance indicators of the rail container transport in India after the process of breaking up the monopoly of the state enterprise CONCOR, identifying the lowest efficiency of the state-owned company during the period analysed. Jitsuzumi and Nakamura (2010) used DEA and the cost-based efficiency model suggested by Farrell (1957) and Debreu (2012) to analyse the causes of inefficiency of the Japanese railways and proposed a method of calculating the optimum level of subsidy to compensate for regional disparities. They concluded that there are railroads that received grants above what was indicated by their model, suggesting that the methodology proposed can bring benefits to public officials. Oum, Pathomsiri and Yoshida (2013) used the nonparametric method Directional Output Distance Function (DODF), a derivative DEA model with the ability to incorporate undesirable outputs, with composite indicators of social efficiency to evaluate the efficiency of the DMUs and they concluded that the railways are more socially efficient than airlines. George and Rangaraj (2008) used the DEA and Super Efficiency DEA (SDEA) methodologies to evaluate the performance of the railway zones of the Indian network and identified what were the zones of better performance and their efficiency trends. Yu (2008), Yu and Lin (2008) and Doomernik (2015) used the Network DEA (NDEA) approach. Yu (2008) assessed production efficiency, service effectiveness, and the efficiency of 40 European railway systems. Yu and Lin (2008) evaluated the efficacy of 20 passenger and cargo railroads selected in the world and Doomernik (2015) used NDEA on the high-speed systems to transport passengers in Asian and European countries. Yu (2008) and Yu and Lin (2008) consider that the methodology allowed greater insights regarding the sources of inefficiency and thus helped improve the performance of the systems. Doomernik (2015) found the most efficient systems of the sample and the factors that contribute to high performance production. Shi, Lim and Chi (2011), Guzman and Montoya (2011), Kabasakal, Kutlar and Sarikaya (2013) and Doomernik (2015) not only analysed efficiency based on the DEA or NDEA models, but they also evaluated the productivity evolution of the American railways, of the Spanish railways, of certain selected railways in the world, and of the HSR systems, respectively, by analysing the evolution of the Malmquist Index. Shi, Lim and Chi (2011) examined the factors of productivity gains of each American railroad, concluding the leadership of Burlington Northern Santa Fé (BNSF) followed by Union Pacific (UP). Guzmán and Montoya (2011) analysed the productivity gains in the Spanish railroads that would explain the next corporate movements in the period analysed. Kabasakal, Kutlar and Sarikaya (2013) analysed the DEA models and the range of productivity of 31 railways in the world and concluded that the small-scale railways set up for non-economic factors (political or ethnic), such as in Spain and Bosnia, are unproductive. Some studies carried out a second stage of the analysis by analysing contextual variables. Hilmola (2011) used a linear regression after applying the DEA model and analysed the relationship between the efficiency scores of the public transport systems and the share of using the individual transport by car in large cities, concluding that there is a significant relationship between the lower modal share of transport by car and the higher efficiency levels of those systems. Kutlar, Kabasakal and Sarikaya (2013) used the Tobit Regression to determine which outputs of the DEA model were significant for the DEA efficiency scores, concluding that the outputs used were more significant to explain the allocative efficiency. Wanke and Barros (2015) estimated efficiency scores in the Brazilian railway industry using Distance Friction Minimization (DFM) and by the Tobit Regression investigated the effects of the contextual variables, location, and type of cargo in these estimates. They concluded that the regulatory authorities should consider two groups of companies for funding with different interest rates on investments in infrastructure: one focused on the transportation of iron ore and the other for the transportation of agricultural commodities and containerized general cargo. Kabakasal, Kutlar and Sarikaya (2013) used a panel regression for analysing the influence of the outputs on the efficiency scores found. They concluded that the CCR model with constant yields of scale offers more significant explanations for the influence of the outputs on the efficiency scores than the BCC model with variable yields of scale where the outputs were not significant. Mallikarjun, Lewis and Sexton (2014) applied non-oriented NDEA to evaluate the efficiency of 24 rail systems of public transportation in the United States during 2001-2010. To evaluate the relationship between inefficiency and subsidies, the Censored Tobit Regression and Generalized Least Squares (GLS) Regression with bootstrapping were used to overcome discussions about nonparametric efficiency measurements. The conclusion was that the highly subsidized systems are, on average, less efficient with respect to operating expenses and tariff revenue compared with those that are less subsidized. Parametric methods were also used for evaluating the railway's efficiency. Crafts, Mills and Mulatu (2007) used Total Factor Productivity (TFP), the efficient change, to analyse the British railways' productivity between 1852-1912, concluding the existence of management problems related to collusion and barriers to entry. Leunig, Mulatu and Crafts (2008) used TFP to assess whether the British railways were well managed in the early 20th century. They concluded that the companies were generally not well administered a hundred years ago as they were affected by inefficiency of costs and low growth in the TFP. Neither competition nor regulation were effective. Couto and Graham (2008) used Stochastic Frontier Analysis (SFA) to analyse the efficiency of the European railway transport industry between 1972-1999, concluding the average loss of 15% in efficiency due to higher costs caused by technical (6.5%) and allocative (7%) inefficiency. Kumbhakar et al. (2007) used Latent Class Model (LCM) and panel data from 17 European railroads between 1971-1974. The conclusion was that the orientation by input is preferred after the European directives of 1984 (management by business unit, separating accounts, and each segment costs) to increase the profitability of companies or reduce losses. It was suitable for railways in Spain, Portugal, Greece, and Ireland. The orientation by output was suitable for railways in Switzerland, Luxembourg, Norway, Denmark, and Sweden. Graham (2008) compared the results of efficiency measured with DEA and TFP concluding in the similarity of rankings, despite differences in the returns in scale of the commuter rail companies. Table 3.1 below shows 50 observations of the 21 papers revised and the variables selected in literature that will be the object of the meta-analysis in Section 3.4.

Table 3.1:
Data sheet: papers and variables selected in the literature about railway frontier efficiency.

Observation	Author(s)	Year published	Study location	Type of service	Number of DMUs (NDMUs)	Type of model	Mean efficiency (%)	Number of variables (NVAR)	NDMUs/ NVAR (log)	Database structure (DB)
1	Wanke,P._and_Barros,C.P.	2015	Brazil	conv_cargo	90	NON_PARAM	0.652	7	1.1	0
2	Bhanot,N._and_Singh, H.	2014	India	conv_cargo	18	NON_PARAM	0.838	7	0.4	0
3	Bhanot,N._and_Singh, H.	2014	India	conv_cargo	18	NON_PARAM	0.875	7	0.4	0
4	George,S.A._and_Rangaraj,N.	2008	India	conv_pax_cargo	16	NON_PARAM	0.821	4	0.6	0
5	George,S.A._and_Rangaraj,N.	2008	India	conv_pax_cargo	16	NON_PARAM	0.870	4	0.6	0
6	Kabakasal,A._et_al	2013	Worldwide	conv_pax_cargo	31	NON_PARAM	0.919	11	0.5	0
7	Kabakasal,A._et_al	2013	Worldwide	conv_pax_cargo	31	NON_PARAM	0.969	11	0.5	0
8	Kutlar,A._et_al	2013	Worldwide	conv_pax_cargo	31	NON_PARAM	0.919	11	0.5	0
9	Kutlar,A._et_al	2013	Worldwide	conv_pax_cargo	31	NON_PARAM	0.969	11	0.5	0
10	Guzman,I._and_Montoya,J.L.	2011	EU	conv_pax_cargo	90	NON_PARAM	0.875	5	0.6	0
11	Hilmola,O-P	2007	EU	conv_cargo	25	NON_PARAM	0.405	5	0.7	0
12	Hilmola,O-P	2007	EU	conv_cargo	25	NON_PARAM	0.319	5	0.7	0
13	Shi,F.X._et_al	2011	US	conv_cargo	42	NON_PARAM	0.880	7	0.8	0
14	Hilmola,O-P	2011	Worldwide	conv_pax	52	NON_PARAM	0.647	7	0.8	1
15	Hilmola,O-P	2011	Worldwide	conv_pax	52	NON_PARAM	0.597	7	0.8	1
16	Hilmola,O-P	2011	Worldwide	conv_pax	43	NON_PARAM	0.697	10	0.6	1
17	Hilmola,O-P	2011	Worldwide	conv_pax	43	NON_PARAM	0.795	10	0.6	1
18	Doomernik,J._E.	2015	Worldwide	HSR	48	NON_PARAM_2	0.866	3	1.2	0
19	Doomernik,J._E.	2015	Worldwide	HSR	48	NON_PARAM_2	0.875	4	1.1	0
20	Doomernik,J._E.	2015	worldwide	HSR	48	NON_PARAM_2	0.941	3	1.2	0
21	Doomernik,J._E.	2015	worldwide	HSR	48	NON_PARAM_2	0.911	4	1.1	0
22	Oum,T.H._et_al	2013	Japan	conv_pax	45	NON_PARAM	0.992	6	0.7	0
23	Yu,M-M	2008	worldwide	conv_pax_cargo	40	NON_PARAM	0.756	8	0.7	1
24	Yu,M-M	2008	worldwide	conv_pax_cargo	40	NON_PARAM_2	0.807	6	0.8	1
25	Yu,M-M	2008	worldwide	conv_pax_cargo	40	NON_PARAM_2	0.479	5	1.0	1
26	Yu,M-M	2008	worldwide	conv_pax_cargo	40	NON_PARAM_2	0.673	6	0.8	1
27	Yu,M-M_and_Lin,E.T.J.	2008	worldwide	conv_pax_cargo	20	NON_PARAM_2	0.742	6	0.5	1

Table 3.1: Continued.

Observation	Author(s)	Year published	Study location	Type of service	Number of DMUs (NDMUs)	Type of model	Mean efficiency (%)	Number of variables (NVAR)	NDMUs/ NVAR (log)	Database structure (DB)
28	Yu,M-M_and_Lin,E.T.J.	2008	worldwide	conv_pax_cargo	20	NON_PARAM_2	0.864	5	0.7	1
29	Yu,M-M_and_Lin,E.T.J.	2008	worldwide	conv_pax_cargo	20	NON_PARAM_2	0.838	6	0.5	1
30	Bil,J.	2013	EU	conv_pax_cargo	23	NON_PARAM	0.682	6	0.6	1
31	Bil,J.	2013	EU	conv_pax_cargo	23	NON_PARAM	0.807	6	0.6	1
32	Bil,J.	2013	EU	conv_pax_cargo	23	NON_PARAM	0.6	6	0.6	1
33	Crafts,N._et_al.	2007	EU	conv_pax_cargo	61	PARAM	0.734	6	1.0	0
34	Crafts,N._et_al.	2008	EU	conv_pax_cargo	126	PARAM	0.924	6	1.7	0
35	Graham,D.J.	2008	worldwide	conv_pax	89	NON_PARAM	0.44	4	1.4	0
36	Graham,D.J.	2008	worldwide	conv_pax	89	NON_PARAM	0.5	4	1.4	0
37	Kumbhakar,S.C._et_al.	2007	EU	conv_pax_cargo	408	PARAM	0.819	6	1.8	0
38	Kumbhakar,S.C._et_al.	2007	EU	conv_pax_cargo	408	PARAM	0.799	6	1.8	0
39	Kumbhakar,S.C._et_al.	2007	EU	conv_pax_cargo	408	PARAM	0.888	6	1.8	0
40	Kumbhakar,S.C._et_al.	2007	EU	conv_pax_cargo	408	PARAM	0.901	6	1.8	0
41	Jitsuzumi,T._and_Nakamua,A.	2010	Japan	conv_pax	318	NON_PARAM	0.618	4	1.9	1
42	Jitsuzumi,T._and_Nakamua,A.	2010	Japan	conv_pax	318	NON_PARAM	0.44	4	1.9	1
43	Mallikarjun,S._et_al.	2014	US	conv_pax	24	NON_PARAM_2	0.819	2	2.1	0
44	Mallikarjun,S._et_al.	2014	US	conv_pax	24	NON_PARAM_2	0.979	2	2.1	0
45	Mallikarjun,S._et_al.	2014	US	conv_pax	24	NON_PARAM_2	0.908	2	2.1	0
46	Mallikarjun,S._et_al.	2014	US	conv_pax	24	NON_PARAM_2	0.804	2	2.1	0
47	Couto,A._et_Graham,D.J.	2008	EU	conv_pax_cargo	756	PARAM	0.938	11	1.8	0
48	Couto,A._et_Graham,D.J.	2008	EU	conv_pax_cargo	756	PARAM	0.95	11	1.8	0
49	Couto,A._et_Graham,D.J.	2008	EU	conv_pax_cargo	756	PARAM	0.947	11	1.8	0
50	Couto,A._et_Graham,D.J.	2008	EU	conv_pax_cargo	756	PARAM	0.961	11	1.8	0

Type of model: NON PARAM = DEA, SDEA, DODF, DFM, SBM; NON_PARAM_2 = NDEA; PARAM = TFP, SFA, LCM; DB = panel data [1]; cross-section [0]
DMUs = Decision Making Units
Type of service: conventional cargo = conv_cargo; conventional passenger and cargo = conv_pax_cargo; conventional passenger = conv_pax; HSR technology = HSR.

Studies on meta-analysis have been reported in the literature in various fields, especially in education, medicine, psychology, and nursing. The ones in the transportation sector are presented for methodological and findings references. Castillo-Manzano and Castro-Nuño (2012) carried out a meta-analysis of the effects of adopting the system of points on drivers' licenses in road accidents and the duration of the effects. The authors concluded that there are strong initial effects (15 to 20% reduction of accidents, fatalities, and losses) that seem to disappear after 18 months. Nocera, Tonin and Cavallaro (2015) investigated the economic impact of GHG reduction in 60 studies. They evaluated the variation in the emission costs to statistically reduce the uncertainty of the amounts. Through a meta-regression it was found that the discount rate adopted is statistically significant for the results. Limiters for the meta-analysis were also reported by Cavill et al. (2008) who have made a systematic review of the economic analysis that include health effects related to cycling and walking. Since there was a wide variety in the approaches taken by the authors, a lack of transparency was found, and the meta-analysis could not be done. Wardman, Chintakayala and De Jong (2016) conducted an extensive meta-analysis of value of time from 389 European studies and 26 European countries. The meta-model estimated, among other items, mean values of commuting, business, other and all kinds of trips, contrasting to official values. They reached the conclusion that the difference between meta-model estimates and official values is far from statistically significant. Dimitropoulos, Rietveld and Van Ommeren (2013) performed a meta-analysis with 33 studies that investigated consumer preferences for electric and other alternative fuel vehicles. They reached the conclusion that consumers are willing to pay on average between US$ 66 and US$ 75 of capital cost for a one-mile increase in driving range. Mohammad et al. (2013) conducted a meta-analysis on 23 studies that analysed the impact of rail on land/property value changes. They reached the conclusion that commuter rail was found to have higher impacts on land/property value changes in comparison to light rail and heavy rail dampened the effect on land/property values compared to light rail. They also found that the impact of rail on land/property values was higher in European and East Asian cities compared to cities in North America. Holmgren (2007) applied meta-regression to explain the wide variation in elasticity estimates obtained in previous demand studies. He concluded that demand models should include car ownership, price of fuel, income, and some measure of service among the explanatory variables. Odeck and Bråthen (2012) present a meta-analysis of variations in seaport mean technical efficiency scores based on 40 studies published in refereed academic journals. They encouraged the use of random-effects models. Using a Tobit Regression model, they reached the conclusion that studies that used nonparametric DEA models depict higher mean technical efficiency ($\overline{TE}$) scores compared with those that used SFA models, panel data studies have lower $\overline{TE}$ scores as compared with cross-sectional data, and studies using European seaport data produce lower $\overline{TE}$ scores when compared with the rest of the world. Brons et al. (2005), considered the first meta-analysis in transport (ODECK; BRÅTHEN, 2012), explained the statistical variation in efficiency findings reported in the literature. They used OLS (Ordinary Least Squares) and WLS (Weighted Least Squares) regression models and reached the conclusion that the type of database, region, and the output measurement method influence technical efficiency. Results showed that there is no statistical difference in technical efficiency between parametric and nonparametric studies and that there is a positive univariate relationship between the number of inputs and the efficiency ratio.

As to our best knowledge, it is the first time meta-analysis is used to aggregate and contrast the results of studies on efficiency frontier of railways in its most different methods and characteristics to identify findings on how the variables used by the researchers affect the results found in these studies. Although studies with meta-regression have already evaluated the effect of variables selected on the dependent variable (BRONS et al., 2005; KABASAKAL; KUTLAR; SARIKAYA, 2013; NOCERA; TONIN; CAVALLARO, 2015; ODECK; BRÅTHEN, 2012; THIAM; BRAVO-URETA; RIVAS, 2001), this paper, following Viechtbauer (2010), used a permutation test, a process that is random, with repetition, thus overcoming limitations as to the normal distribution of the dependent variable and other potential sources of misleading results in meta-analyses (see more in subsection 3.4.1).

3.2.1 Characteristics and Limitations of the Methods

A brief set of the main technical characteristics that differs efficiency models are summarized in order to prepare the reader to follow the meta-analysis purposes. DEA and SFA methodologies are two of the techniques most used in estimating efficiency frontiers (FIORENTINO; KARMANN; KOETTER, 2006; HJALMARSSON; KUMBHAKAR; HESHMATI, 1996; ODECK; BRÅTHEN, 2012). DEA is a deterministic and nonparametric method introduced by Charnes, Cooper and Rhodes (1978) based on linear programming (BOGETOFT; OTTO, 2011; DERVAUX; KERSTENS; VANDEN EECKAUT, 1998; VITON, 1997) that estimates the best practices of the efficiency frontier, evaluating the relative efficiency of the firms (BOGETOFT; OTTO, 2011). SFA is a stochastic and parametric method based on the econometric theory that assumes that deviations from the frontier may reflect not only inefficiencies but also the existence of random error in the data estimate (BOGETOFT;

OTTO, 2011), statistical error or other non-systematic influences (AMORNKITVIKAI; HARVIE, 2010). Efficiency estimates vary considerably between studies (FIORENTINO; KARMANN; KOETTER, 2006). In some studies, the SFA estimates are substantially higher than with DEA (FIORENTINO; KARMANN; KOETTER, 2006), sensitive to heterogeneity and errors in the database (KHEZRIMOTLAGH, 2013) because of the presence of heterogeneous observations that affect the average efficiency in a more intense way than in the SFA methodology. In some studies, however, the estimates using DEA were higher than estimates with SFA (KUCHLER, 2013). Ekanayake and Jayasuriya (1985) indicate that the deterministic frontiers tend to overestimate the inefficiency in relation to the stochastic frontiers. This is not surprising since the deterministic estimates attribute all errors to inefficiency (BRONS et al., 2005). Bogetoft and Otto (2011) indicate that there is a tendency for efficiency estimates using DEA to be greater than estimates using SFA for higher efficiency levels and the opposite for lower efficiency levels. Overall, the experiences are definitely not conclusive. Some authors, however, argue that there are no significant differences between the methods and that there is not only one method to properly evaluate the efficiency frontier. They view these methodologies as complementary rather than competing (KUCHLER, 2013). NDEA methodology considers the system composed of different processes or stages, each with its own inputs and outputs and intermediate flows between stages. Lozano, Gutiérez and Luís (2009) consider the NDEA methodology as having more discriminating power than the conventional DEA methodology because it allows for a more detailed analysis of the entire production process. SDEA, developed by Andersen and Petersen (1993), is a method that seeks to differentiate the DMUs on the efficiency frontier (BOGETOFT; OTTO, 2011). It is especially interesting when several DMUs are on the efficiency frontier and their differentiation is of interest to the researcher. The DF model describes how far or close an element is from the frontier, first introduced by Chambers, Chung and Färe (1998) and the additive model of Charnes et al. (1985) (ADLER; MARTINI; VOLTA, 2013). The DFM approach, developed by Suzuki et al. (2010), serves to improve the performance of a DMU by identifying the most appropriate movement towards the efficiency frontier surface based on a Euclidean distance metric in weighted spaces. SBM is a measure of efficiency considering minimizing the inputs and maximizing the outputs simultaneously (COOPER; SEIFORD; TONE, 2006). In the SBM frontier, the DMU is completely effective if, and only if, better inputs or outputs are not possible without worsening another input or output (COOPER; SEIFORD; TONE, 2006), considering that the Pareto-Koopmans efficiency frontier is not always guaranteed in the classic DEA models. Lastly, the LCM is a stochastic model assuming that heterogeneity exists in the sample that suggests different production technologies adopted within the sample. The frontier production set measures the difference between inefficient units and the frontier through residuals (errors), which have two components: noise and inefficiency.

3.3 METHODOLOGY: A META-ANALYSIS

3.3.1 Search, Exclusion Criteria, and the Literature Review Results (Coding Process)

Some criteria were used to systematically review the literature. We selected recent papers published on efficiency of railways (from 2000 until 2016) pertaining to well-known databases (Proquest, Science Direct, Web of Science) and from Emerald journals, justifying the quality of the papers. The characteristics from each study selected were registered: title, author(s), year published, author's country, study location, and study object. We selected a list of common variables applied in each study: rail service offered (infrastructure), number of railways evaluated (decision making units), efficiency model applied, number and type of inputs and outputs considered, database structure, model orientation, second stage analysis (if any), and second stage model (if any). We calculated the mean efficiency found considering the efficiency modelling developed in each study. Table 3.1, in Section 3.2, summarizes the data from the studies selected. The objective pursued is to examine patterns of evidence of the relationship between study features and the mean efficiency found, verifying what is the effect size (the direction, the size, and the statistical significance) over the mean efficiency. Effect size is used in literature to denote the variable chosen for meta-analysis (VIECHTBAUER, 2010). A meta-analysis often uses multiple results drawn from the same study, a technique also used in this study. Subsection 3.4.4 will treat this issue when conducting the validation methods.

After a brainstorm, the initial keywords used to search the relevant literature were: "transport", "efficiency", "DEA", and "SFA", techniques most used in estimating efficiency frontiers (FIORENTINO; KARMANN; KOETTER, 2006; HJALMARSSON; KUMBHAKAR; HESHMATI, 1996; ODECK; BRÅTHEN, 2012), and "TFP", a technique also commonly used. Studies collected without an efficiency evaluation model were excluded. Efficiency studies of a transport mode other than railways were excluded. The keyword "railways" was, then, included to refine the search. Studies conducted with financial variables, cost-based or without an efficiency scoring available were excluded. There is a publication bias since only published papers were selected. Figure 3.2 shows the flowchart with the results of the systematic review.

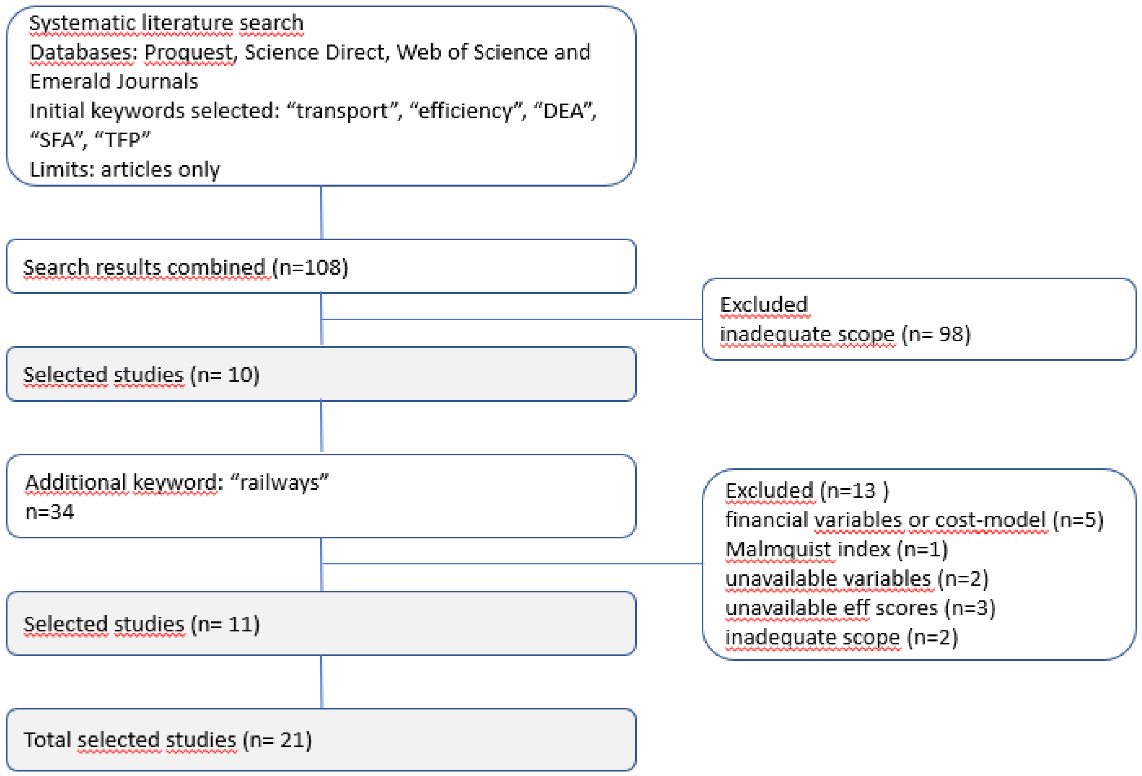

Figure 3.2: Prisma flow diagram of the 21 studies selected (LIBERATI et al., 2009)

3.3.2 The Selection Model Decision

This paper will adopt the random effects model because the studies differ from each other because of different methodologies, constructs, and variables used by the authors. When studies are gathered from published literature, the random effects model is generally a more plausible match (BORENSTEIN et al., 2009). In this empirical study, the dependent variable is the mean efficiency estimates in each of the studies. This possibility has already been previously used in Thiam, Bravo-Ureta and Rivas (2001), Brons at al. (2005), and Odeck and Bråthen (2012). The independent variables are as follows: the railway's geographic location, the type of service offered, the type of model used, the NVAR, the ratio between NDMUs and NVAR, and type of database. Hypothesis tests carried out in Subsection 4.2 seek to elucidate an important part of the variance (KULIK; KULIK, 1989) found in the mean efficiency scores between the studies. The intention was not to explain the totality of the variance, translated into tau^2 (BORENSTEIN; HEDGES; ROTHSTEIN, 2007), which would require numerous other possibilities. This research aimed only to find statistical significance of common variables used in previous studies that contributed to elucidate the research questions.

3.4 ANALYSIS OF THE DATABASE AND DISCUSSION OF RESULTS

3.4.1 Database and Model Fitting

Table 3.1 presents 50 observations from 21 papers on efficiency frontier of railways developed in different regions with 10 different methodologies. The structure of the analysis was in a way similar to inputs, production process, and outputs being considered in the estimate of relative efficiency of the DMUs (DERVAUX; KERSTENS; VANDEN EECKAUT, 1998; FÄRE; KNOX LOVELL, 1978; VITON, 1997). Some studies reported more than one efficiency model.' The number of observations taken from the same study was a concern since using many observations from the same study could introduce a bias and invalidate the hypothesis tests. This issue is treated in subsection 3.4.4.

The studies were developed on railroads located in Brazil, US, UK, countries of the European Community, China, India, Japan, and Taiwan. Some authors assessed the relative efficiency of railways in different parts of the world together. In this case we used the world as the location factor. Some articles analysed only European railroads. In this case, EU was used as the location factor. The aim was to test the hypothesis of there being any evidence or characteristic in some region that contributes to explain the mean efficiency. Subsection 3.2.1 presented the characteristics and limitations of the various techniques that have been used to evaluate the efficiency frontier of railways. There are studies in literature that compare methodologies (AMORNKITVIKAI; HARVIE, 2010; BOGETOFT; OTTO, 2011; FIORENTINO; KARMANN; KOETTER, 2006; HJALMARSSON; KUMBHAKAR; HESHMATI, 1996; KUCHLER, 2013). In this study, the techniques have been grouped into parametric and nonparametric models to compare the results obtained with what the literature would indicate. Additionally, among the nonparametric techniques, it was highlighted the studies that used the NDEA methodology that better detail the production process flow. The objective was to test the hypothesis of a statistical difference between the results with nonparametric models including DEA and with NDEA methodology. Another highlight was the variable type of service offered, which included the factors conventional cargo, conventional cargo and passengers, conventional passengers, and HSR. The aim was to test whether the type of service significantly influences the mean efficiency found. It was a concern of this study if there is a high correlation between the factors location and type of service. Railways in Japan are predominantly passenger services railways while in the US and Brazil they are predominantly freight railways. In the EU and India and in different parts of the world, however, one has to identify the type of service of each railway, as there are different kinds of services offered in the region. Thus, it was assumed that there is not a high correlation between the location and the type of service of the railway. The NVAR used by each author and the relationship between NDMUs and NVAR in each of the researches were also selected. The aim was to test and analyse the significance of these quantitative variables in the mean efficiency scores obtained. Finally, the structure of the database used was highlighted in the factors panel data or cross-section (BRONS et al., 2005; ODECK; BRÅTHEN, 2012; THIAM; BRAVO-URETA; RIVAS, 2001) to test the significance of the data structure in the values of mean efficiency. Table 3.2 summarizes the contextual variables selected.

Table 3.2:
Common contextual variables selected from studies of efficiency frontier of railways.

Method used	Location of study	Type of service
Nonparametric (DEA, DFM,	Brazil	Conventional cargo
DODF, SDEA, SBM, DF)	EU	Conventional cargo and
Nonparametric 2 (NDEA)	US	passengers
Parametric (TFP, SFA, LCM)	Japan	Conventional passengers
	World	HSR

DEA = Data Envelopment Analysis; DFM = Distance Friction Minimization; DODF = Directional Output Distance Function; SDEA = Super Efficiency DEA; SBM = Slack Based Measure; DF = Distance Function; NDEA = Network DEA; TFP = Total Factor Productivity; SFA = Stochastic Frontier Analysis; LCM = Latent Class Model.

Table 3.3 shows the heterogeneity test summary of the efficiency frontier studies on railways. The hypothesis of heterogeneity was accepted, confirmed by the value of tau^2 (variance between studies).

Table 3.3:
Sample's heterogeneity test (Q).

Estimator	Amount	Comment
Q	1,541.3	Estimator
p-value	0.0001	Rejected Ho
tau^2	0.2365	Variance between studies
Df	49	Degrees of freedom
I^2	96.8%	% of total variability due to heterogeneity

DSL (Dear Simonian-Laird) estimator for tau^2.

Figure 3.3 shows the funnel plot (LIGHT; PIELLEMER, 1984; VIECHTBAUER, 2010) of the studies considered in the sample (numbered 1 to 50) and shows the dispersion found of the mean efficiency between the studies (articles outside the dotted funnel). On the horizontal axis are the values observed of mean efficiency estimates (Fisher’s transformed) and on the vertical axis are the corresponding standard errors (SE). More details can be accessed at Schwarzer, Carpenters and Berta (2015) and Howard (2016). The studies located outside the dotted funnel plot are those studies considered heterogeneous in the sample. Heterogeneous studies may contain information, attributes or characteristics that can help explain an important part of the variance found in the mean efficiency scores.

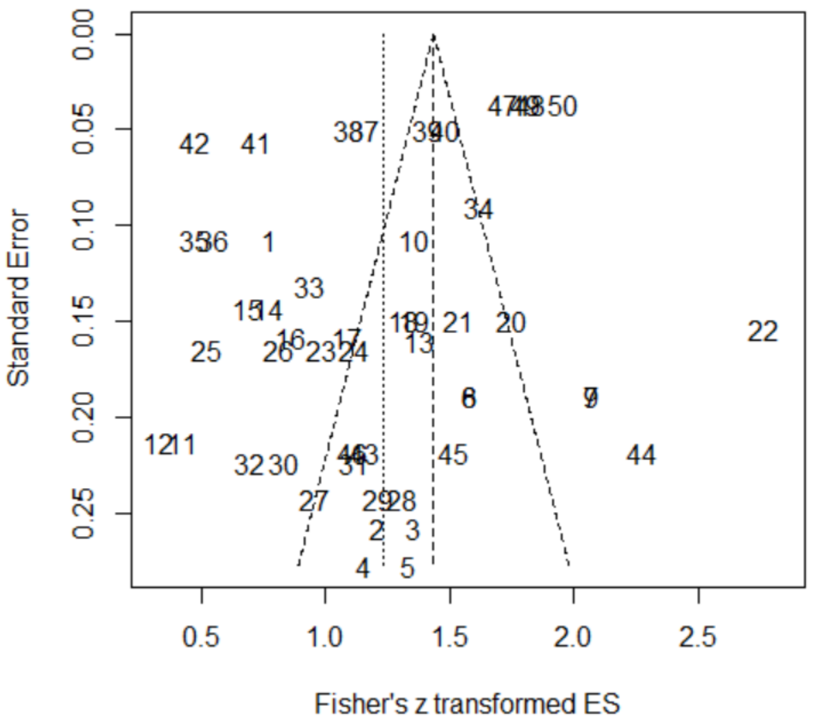

Figure 3.3: Funnel plot of the 50 observations present in the 21 studies on the efficiency frontier of railways

Figure 3.4 shows the forest plot or the confidence interval chart. The studies are identified by the author and year published (Study column) and by the NDMUs used (Total column). The mean efficiency scores of each study is represented by the point on each line representing the confidence interval (95%-CI) for the mean efficiency of each study. In the fixed effects meta-analysis, studies with a higher number of DMUs receive a higher weight, differently from a random effects model, which is much more homogenous.

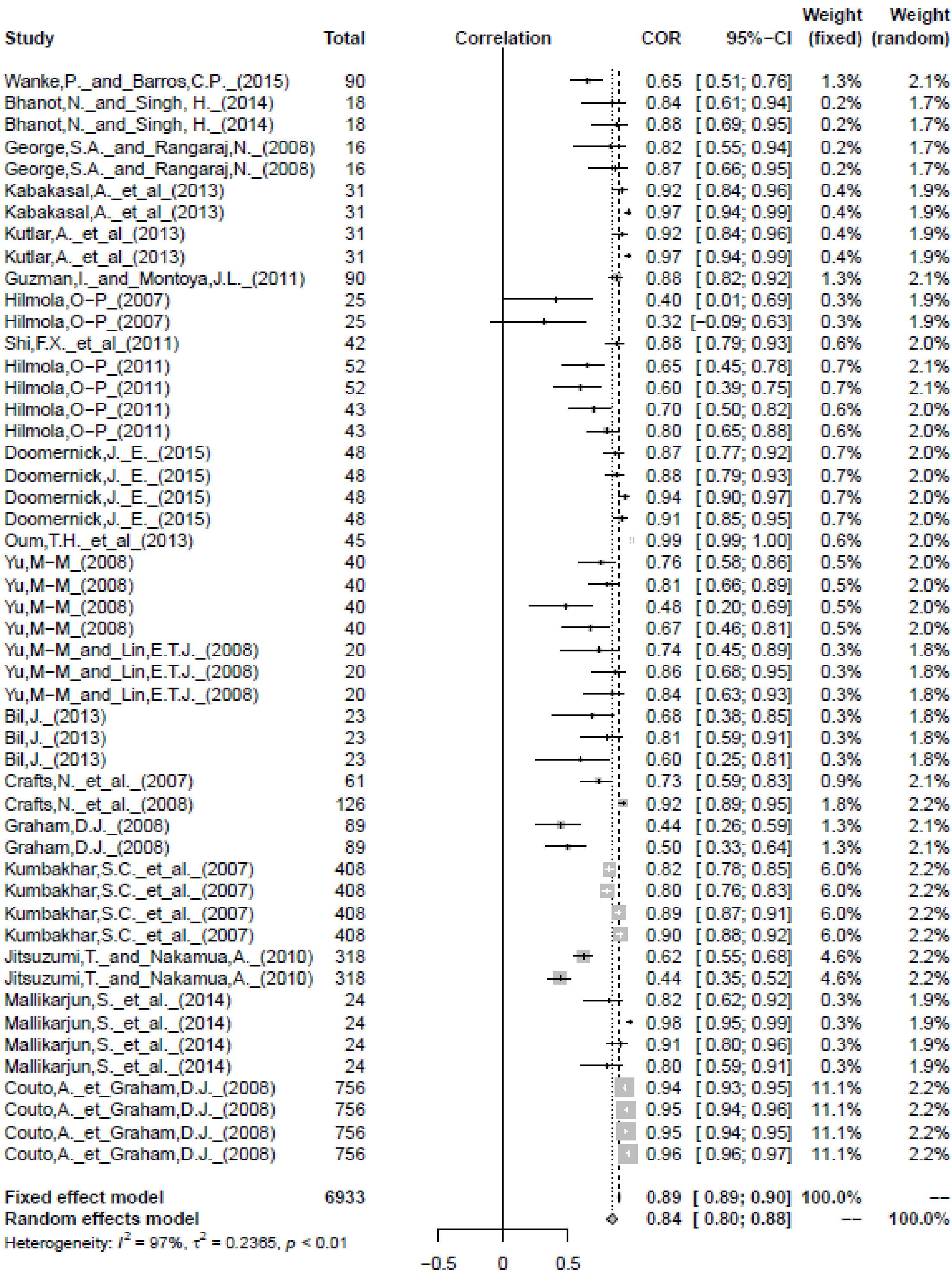

Figure 3.4: Forest plot of the 50 observations present in the 21 studies on the efficiency frontier of railways

Numerous meta-analysis models were structured before defining the final model, which followed the comprehensive literature terms. The advantage of the model proposed by (VIECHTBAUER, 2010) is that it does not impose limitations for analysis of independent variables (moderators), which facilitates the search for insights about the impact of several characteristics present in the structure of the studies selected. The significance of the variables selected were tested by a meta-regression linear model to examine the influence of variables on the mean efficiency. The following meta-regression structure was used:

$$\overline{TE}=\beta_0 + \beta_1.\text{LOCATION} + \beta_2.\text{TYPE OF SERVICE} + \beta_3.\text{MODEL TYPE} + \beta_4.\text{NVAR} + \beta_5.\text{NDMUs/NVAR} + \beta_6.\text{DB} + \xi \quad (1)$$

where,

$\overline{TE}$ (mean technical efficiency) is the mean efficiency of the DMUs found in each study. LOCATION is the variable that denotes the country or geographic location where the study was developed (factors = Brazil, EU, India, Japan, US or *world*). TYPE OF SERVICE is the variable that denotes the type of service offered on the set of railways analysed (factors = conventional cargo, conventional cargo and passengers, conventional passengers or HSR). MODEL TYPE is the variable that explains the model used by the researcher to evaluate the estimates of $\overline{TE}$ (factors = nonparametric, nonparametric 2 [NDEA], or parametric models). NVAR is the number of variables used in each research. NDMUs/NVAR is the ratio between those variables. DB is a variable that takes the value 1 for panel data and 0 for cross-section, while ξ is the error term.

Equation (1) can be depicted as follows:

$$\overline{TE}=\beta_0 + \beta_1.LOCATION\ [Brazil] + \beta_2.LOCATION\ [EU] + \beta_3.LOCATION\ [India] + \beta_4.LOCATION\ [Japan] + \beta_5.LOCATION\ [US] + \beta_6.TYPE\ OF\ SERVICE\ [conventional\ passanger] + \beta_7.TYPE\ OF\ SERVICE\ [conventional\ passanger\ and\ cargo] + \beta_8.TYPE\ OF\ SERVICE\ [HSR] + \beta_9.TYPE\ OF\ MODEL\ [non\ parametric\ 2\ (NDEA)] + \beta_{10}.TYPE\ OF\ MODEL\ [parametric] + \beta_{11}.NVAR + \beta_{12}.NDMUs/NVAR + \beta_{13}.DB\ [panel\ data] + \xi \quad (2)$$

A nonparametric permutation test was used as suggested by Higgins and Thompson (2004) and Follmann and Proschan (1999) to overcome the distribution restriction of the dependent variable, which is not always guaranteed with linear models of OLS or WLS Regression (normality restriction) or of Tobit Regression (censorship restriction of the dependent variable scores). The authors suggested permutation tests of the model coefficients as an alternative approach to the standard tests, which assume normality of the dependent variable and rely on the asymptotic behaviour of the parametric test statistics (Wald and likelihood ratio). The two-sided p-value for a particular model coefficient is then equal to twice the proportion of times that the test statistic for the coefficient under the permuted data is as extreme or more extreme than under the data actually observed (VIECHTBAUER, 2010). It is expected that the permutation-based results lead to more conservative (larger) values of pval than in the original meta-regression (VIECHTBAUER, 2010).

Higgins and Thompson (2004) showed that the permutation test reduces the rates of false-positive findings from meta-regression in the presence of heterogeneity, a small number of studies or many covariates resulting from correlation between study characteristics, which are typical situations on meta-regressions. Although the risk of identifying a spurious association decreases with the increasing of the number of studies, it is unclear at what point the risk became acceptable. The algorithm proposed by Higgins and Thompson for the permutation test with one covariate (or a moderate $[m]$ number of covariates) involves randomly re-allocating the pairs $\{y_i, v_i\}$, the dependent variable of the meta-regression and its corresponding variance, to covariate values by randomly permuting the indices i=1, …, k in the pairs $\{y_i, v_i\}$. Then, performing the meta-regression and collecting the order T statistic test |T|, the effect of a particular covariate via a Wald test (or $T^{(1)}$, $T^{(2)}$,…, $T^{(m)}$, from the most significant to the least significant covariate, for $[m]$ covariates). Repeating this process N times, the next step is to compare $|T_{orig}|$ (or the ordered $T_{orig}^{(1)}, T_{orig}^{(2)} \dots T_{orig}^{(m)}$ for $[m]$ covariates), calculated with the original data, with |T| (or the ordered collection of $|T^{(1)}|$s, $|T^{(2)}|$s,…, $|T^{(m)}|$s for $[m]$ covariates) and determine n, the number of statistics |T| that equal or exceed $|T_{orig}|$. The permutation test p-value for the meta-regression is n/N for each covariate. See Higgins and Thompson for more details.

3.4.2 The Validity of the Use of the Mean Technical Efficiency as a Dependent Variable in Meta-Analysis

The study comparability was a concern in literature when the dependent variable of the meta-analysis is the observed (mean) efficiency scores of individual firms in different environments. The previous discussion suggests that, as technical efficiency (TE) is a relative measure, comparing average TE values ($\overline{TE}$) between studies may lead to biased results.

Let's assume that each study is delimitated by a production possibility set with its own technology, environment (e.g. location, the type of service, the type of model, sample size, number of variables and the type of the database) and efficiency frontier. That's the situation A in Figure 3.5. Let's consider more than one study in a different environment. Another efficiency frontier with its own characteristics can be defined. That´s the situation B in Figure 3.5. Let's assume now that there is an actual frontier, not observed, encompassing all study frontiers, represented by the situation C in Figure 3.5. A common actual frontier with an unrestricted technology set that surrounds the elements of any frontier production function operating under different technologies, where $\overline{TE}$ values can be related. If the heterogeneity among the observations is low (homogenous sample A), $\overline{TE}$ should be higher in sample A than from heterogenous sample B. Independently of the values of TE scores of each firm in the situation A or B. Comparing reported $\overline{TE}$ means comparing values that consist of a heterogeneity component and a TE component (BRONS et al., 2005). $\overline{TE}$ score does have information of the heterogeneity of the samples (studies). Under the theoretical assumption that there is some efficiency frontier with universal validity, it is not (in)efficiency values that we are comparing but rather sample heterogeneity.

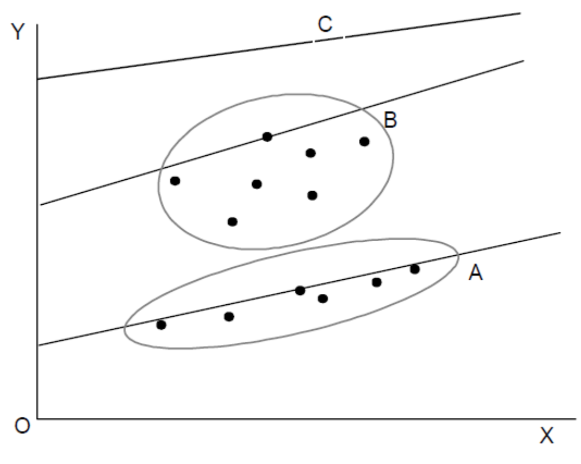

Figure 3.5: Comparison of mean TE values from different studies.
X, Y are one input and one output.
Source: Brons et al. (2005).

Following Brons et al. (2005), a way to circumvent the comparability problem involves a re-interpretation of the dependent variable. Although the actual TE frontier is not observed, average TE value does provide an indication of the relative variation in TE values, and thus of the possibilities to improve TE. If the dependent variable is interpreted as such, then comparison between studies in a meta-analytical format is indeed valid (BRONS et al., 2005). That's the aim of the actual study. To discuss the heterogeneity of the mean efficiency scores between the studies by the variation of the contextual variables, not the (in)efficiency values of individual firms. To interpret part of the heterogeneity embedded on the $\overline{TE}$ values, permitting insights of how the firms can improve efficiency considering relative performances (in different frontiers) to an actual frontier. There will be always conditions to improve efficiency considering the relative situation with an actual frontier.

3.4.3 Empirical Results

Table 3.4 below shows the results found with the estimate of coefficients and the significance of each of the variables selected. The QM is the value of the omnibus test of the model parameters (df=13, excluding the intercept) based on an $\chi 2$ distribution with m degrees of freedom (m being the number of coefficients tested) (VIECHTBAUER, 2010).

Table 3.4:
Model results: estimates and signif. codes of moderators.

Moderators	Estimates	pval*	signif. code
Intercept	0.4276	0.6670	
factor LOCATION [Brazil]	0.2923	0.1030	
factor LOCATION [EU]	0.0265	0.7830	
factor LOCATION [India]	0.2353	0.1330	
factor LOCATION [Japan]	0.2111	0.0280	*
factor LOCATION [US]	0.4866	0.0050	**
factor TYPE OF SERVICE [conv pax]	0.2644	0.0460	*
factor TYPE OF SERVICE [conv pax_cargo]	0.3626	0.0140	*
factor TYPE OF SERVICE [HSR]	0.5749	0.0080	**
factor MODEL [NON PARAM_2 (NDEA)]	0.0416	0.7120	
factor MODEL [PARAMETRIC]	0.2453	0.0780	.
NVAR	0.0206	0.0030	**
NDMUs/NVAR	-0.1909	0.0380	*
DB (panel data [1])	-0.0874	0.2320	

test of moderators (coefficient(s) (2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14)
QM = 141.3667 (df = 13), p-val*=0.0010
signif. codes: '***' 0.1%; '**' 1%; '*' 5%; '.' 10%.

The variable LOCATION was statistically significant to explain part of the variation found in the mean efficiency estimates. The results indicate that the railways in Japan and the United States have a mean efficiency statistically higher than in the studies that assessed railways in different parts of the world (*world* factor), considering a confidence interval of 5%

(Japan) and 1% (US). These findings indicate that there are operational or locational characteristics that lead to improved performance of the railway passenger transportation companies in Japan and freight transportation in the US. The results suggest that, as highlighted in Section 1, the higher indicators of productivity found in the passenger railways in Japan and the higher ATDF found in the American railways may be factors that could leverage the mean efficiency (CARBAJO; DE RUS, 1991). This can lead to further investigations to confirm the suggested insights. Additionally, the results of the studies on EU railways, which were not statistically different from those found in studies assessing railways from different parts of the world, suggest what is stated by Wheat and Nash (2006) where the railways in Europe still had difficulty in providing a competitive combination of cost and quality and to adapt to the European regulatory guidelines. Such guidelines are aimed at opening the market and putting a greater competitive pressure on the network (KUMBHAKAR et al., 2007; WHEAT; NASH, 2006), especially in countries that have had little progress in advancing reforms (Greece and Ireland) or that have implemented them partially (Finland, France, and Spain) with separation of the operating infrastructure while the management and operation is maintained in the public sector without a competitive selection process (WHEAT; NASH, 2006). The results found in studies done in India and Brazil are not statistically different from the results of the studies assessing railways in different parts of the world. This suggests that both the Indian and the Brazilian systems are still looking for performance improvements and still do not differ statistically, although the coefficients give a positive direction and a certain magnitude (intensity). In the case of Brazil, the transportation of iron ore and agricultural commodities on broad gauge (1.60 m) are elements that leverage the increased efficiency (MARCHETTI; WANKE, 2017). However, no statistical difference was found considering the other types of cargo and track gauges (1.00 m and mixed). In the case of India, notwithstanding the high productivity in passenger transport (Section 1), the results indicate that there was no statistical difference.

The variable TYPE OF SERVICE was statistically significant to explain part of the variation found in mean efficiency. The results indicate that the mean efficiency in the mixed conventional, and mainly of passenger only systems, was statistically superior to the cargo only conventional systems when considering a 5% confidence interval. The HSR systems differ statistically in both direction and magnitude considering a 1% confidence interval. These results were expected in that the rail passenger systems are equipped with operational systems and procedures of signalling, control, and safety that are more sophisticated than the cargo only systems, especially the HSR systems, giving them different conditions for increased efficiency.

It also suggests the ability to operate passenger transport together with freight transport with high productivity, as in Asia (e.g. China) and European systems (e.g. France and Germany).

The variable MODEL TYPE was statistically significant. The results indicate that the parametric modelling was statistically different from the nonparametric models, considering a 10% confidence interval. The positive coefficient indicates higher values of mean efficiency on the parametric models than on the nonparametric models. This suggests that the sensitivity of the DEA nonparametric models in the presence of heterogeneity in the database, of outliers, and the existence of error in the parametric model estimates (KHEZRIMOTLAGH, 2013) may explain this condition (subsection 2.1). Furthermore, the deterministic approach tends to overestimate the inefficiency, affecting the average efficiency scores (BRONS et al., 2005; ODECK; BRÅTHEN, 2012). However, unexpectedly, the mean efficiency found among studies with the NDEA methodology and studies with other nonparametric models, including DEA, were not statistically different. The NDEA modelling allows to systematically and sequentially detail the production process under analysis, thus expecting significantly different results from those found in other nonparametric models, including the DEA. The empirical results did not confirm this difference.

The variable NVAR was statistically significant. The results indicate that there is a positive contribution in the mean efficiency the greater the NVAR. Models with many variables can be more complex and rigid due to lower number of degrees of freedom (NDF) and less reproducible to explain different samples. It suggests the hypothesis of losing its discriminatory power and less rigorous values of mean efficiency (COOPER; SEIFORD; TONE, 2006). Odeck and Bråthen (2012) and Brons et al. (2005) reached this conclusion in a meta-analysis developed with ports and urban public transport, respectively.

The variable NDMUs/NVAR was statistically significant to explain part of the variation found in the mean efficiency, but in an inversely proportional way (negative coefficient). This result was expected. The NDF increases with the NDMUs, but decreases with the NVAR (COOPER; SEIFORD; TONE, 2006). This suggests that when there is growth of the NDMUs or a reduction of the NVAR, the NDF and the discriminatory power of the model increase, thus reducing the scores. The ratio between those variables increases and suggests a negative impact on the mean efficiency scores. The empirical result confirmed the effect.

The variable DB was not statistically significant. The results indicate that the mean efficiency in studies using panel data was not statistically different from those in cross-section studies. The result was not expected since the panel data models assess the efficiency of a system over several years and could be more rigorous in evaluating the mean efficiency, leading to statistical differences not confirmed in this study. The negative sign of the coefficient, however, indicates lower values of mean efficiency, which is in line with Odeck and Bråthen (2012).

3.4.4 Validation: Leave-One-Out Cross-Validation (LOOCV) and Independence of Observations (Weighted Regression)

A cross validation of the results was made. The Leave-One-Out Cross-Validation (LOOCV) was considered adequate because of the size (50 observations) and the singularity of the sample. The method uses the same data to train and to test the regression for each observation. One observation is separated to test, and the other 49 observations were used to train the model. The experiment was repeated 50 times until the last observation was separated. Figure 3.6 presents the comparison between the error term of each observation (difference between the predict and the real scores) of the original and the LOOCV regressions, showing similarity and no irregular behaviour. The larger differences between the error term considering the original and the LOOCV regressions were found in the following studies: 1 (WANKE; BARROS, 2015), 22 (OUM et al., 2013), and 33 (CRAFTS et al., 2007).

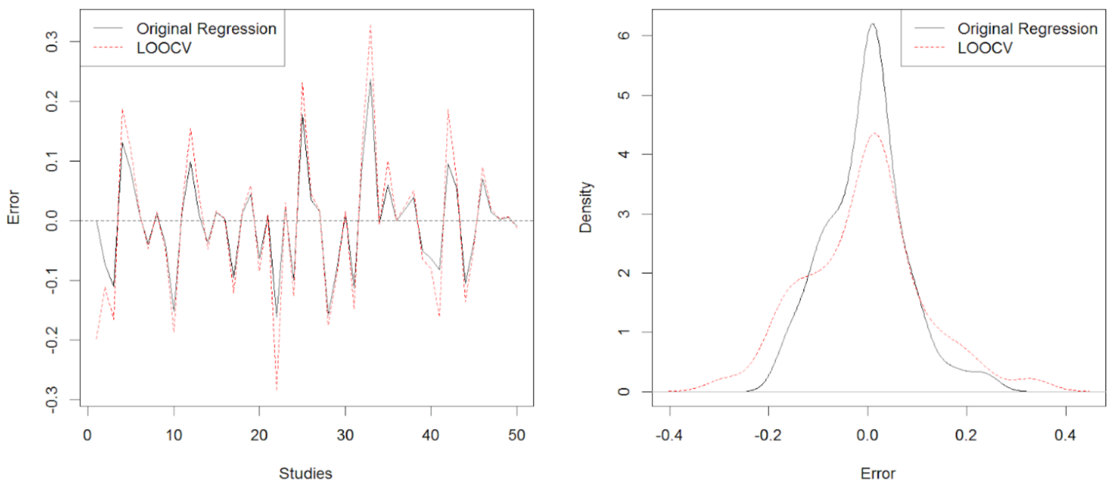

Figure 3.6: Error term and density plot of the original and LOOCV regressions

For the sake of robustness, a weighted regression including the permutation test was conducted considering the inverse of the number of observations of the same study as the weight of each observation of the sample. The aim was to test the effect of using more than one observation per study in predicted results. The results have remained almost the same, except the statistical indifference between parametric and nonparametric models. Additional studies may explore this effect. Table 3.5 shows the results.

Table 3.5:
Estimators and signif. codes of the weighted regression.

Moderators	estimates	pval*	signif. code
Intercept	0.3159	0.851	
factor LOCATION [Brazil]	0.2278	0.121	
factor LOCATION [EU]	0.0511	0.662	
factor LOCATION [India]	0.2501	0.064	.
factor LOCATION [Japan]	0.2881	0.03	*
factor LOCATION [US]	0.3748	0.003	**
factor TYPE OF SERVICE [conv pax]	0.2021	0.086	.
factor TYPE OF SERVICE [conv pax_cargo]	0.2816	0.021	*
factor TYPE OF SERVICE [HSR]	0.518	0.005	**
factor MODEL [NON PARAM_2 (NDEA)]	0.1044	0.339	
factor MODEL [PARAMETRIC]	0.1562	0.315	
NVAR	0.041	0.002	**
NDMUs/NVAR	-0.161	0.062	.
DB (panel data [1])	-0.0907	0.210	

test of moderators (coefficient(s) (2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14)
QM(df = 13) =65.7916, p-val* = 0.001
signif. codes: '***' 0.1%; '**' 1%; '*' 5%; '.' 10%.

3.4.5 Effect on Public Policies

Public policies were implemented to address the drop in performance in rail transport, especially freight, compared to the growth of road transportation in the world, the need for subsidy that is not always transparent in the operations, and the lack of integration and services on international routes (WHEAT; NASH, 2006). Railways, although naturally having economic and environmental competitive advantages over road transport, have struggled to provide a competitive combination of costs and quality (WHEAT; NASH, 2006). In the European community and the US, regulatory mechanisms came into place to ensure the best allocation of resources, improving the efficiency of systems and regaining of market share (CARBAJO; DE RUS, 1991; EUROPEAN POLICY CENTRE, [s.d.]; LEGAL INFORMATION INSTITUTE, [s.d.]; WHEAT; NASH, 2006). They include encouraging competition or competitive pressure in the services (WHEAT; NASH, 2006), removing barriers to enter and exit the passenger and cargo markets (LEGAL INFORMATION INSTITUTE, [s.d.]; WHEAT; NASH, 2006), setting up competitive processes in approving operators (WHEAT; NASH, 2006), ensuring non-discriminatory access, tariffs, and allocation of slots (LEGAL INFORMATION INSTITUTE, [s.d.]), integrating with different means of transport and reducing GHG emissions (EUROPEAN POLICY CENTRE, [s.d.]), introducing new technologies to improve quality (CARBAJO; DE RUS, 1991), giving priority to economic factors and to the financial obstacles in the allocation of resources (CARBAJO; DE RUS, 1991), clarifying the relationship between the State (subsidies) and operators (revenue) (WHEAT; NASH, 2006), and promoting the full exploitation of the technical advantages over road and air transport (CARBAJO; DE RUS, 1991).

The implication of the work could be valuable for railway managers and public agencies that control and regulate rail systems. The empirical results also found suggest reflections of public policy makers as to the regulatory aspects that drive rail transport. The significance of the location factors found suggests that variables such as productivity, traffic intensity, and ATDF are factors likely to increase efficiency. This reiterates the guidelines set out in Carbajo and De Rus (1991) where services must respond to demand and seek to introduce new technologies to improve the quality with a priority to economic factors. These guidelines are characteristics more strongly observed in the Asian systems such as China and Japan, but also Korea and Taiwan and in the European systems, but differently (e.g. the systems in France and Germany have a higher productivity than in Spain), and less observed in the Americas, except in the United States, whose railways have a high ATDF. The existence of subsidized unprofitable lines, not necessarily done in a transparent way, also sets a concern about the efficiency of the operation. Furthermore, the significance regarding the type of service found suggests the importance of the ability of the railway systems to combine passenger transportation with their more complex systems of signalling, control & safety, and cargo transport, as one can observe in higher productive European systems and Asian systems. It can mean improvement in allocating resources and increased efficiency. The result also means an important warning to the American systems, especially in Brazil and US, where there is a predominance or almost exclusive cargo transportation. Efficiency frontier studies showed, in turn, a positive significant influence of mixed transportation service over the mean efficiency. There was no information in the studies selected of the existence of regulatory mechanisms that hinder competition in the various systems analysed such as price discrimination for access to infrastructure or difficulty of allocating slots to third parties, as well as the ownership of each railways, whether private or public or both. It would be interesting for new studies to evaluate the effect of these regulatory variables, which represent barriers to entry, and the effect of the ownership on the mean efficiency of the systems and whether they could explain part of the variance found.

The analyses of efficiency frontiers and the consequent development of company rankings are often used for performance evaluation purposes of many public services carried out by regulatory agencies responsible for monitoring and inspecting operations. The significance of the type of methodology found suggests some aspects that may be of interest to these agencies. Although the NDEA and other nonparametric methodologies including DEA were not significantly different to the average scores of efficiencies, this result should be viewed with parsimony. It is not just about the statistical difference between the mean scores. Knowledge of the effectiveness of each part of the flow of the production process by applying the NDEA methodology can better direct specific actions in pursuit of efficiency. Moreover, when the nonparametric widely used DEA methodology loses discrimination power by increasing the NVAR (COOPER; SEIFORD; TONE, 2006), by the heterogeneity of data, and/or the presence of outliers (KHEZRIMOTLAGH, 2013), then a complementary evaluation method can be used. This corroborates the above in Kuchler (2013) that evaluates the DEA (nonparametric) and SFA (parametric) methods more as complementary than as competitive models and as being able to understand better the efficiency results found. Finally, the modelling used by these agencies should be conscious about the increase in NVAR. The growth of this variable is significant in the results of efficiency and can impose greater rigidity and complexity to the methodology, which may become undesirable for assessing the efficiency of public services.

3.5 CONCLUSIONS

The research sought to address, through meta-analysis followed by a permutation test, a production process that to the best of our knowledge had never been investigated in the literature. From a systematic review of articles assessing the efficiency frontier of the railway systems, this paper aimed at obtaining results not identified in each study individually that may explain part of the variance found in the mean efficiency estimates between surveys. Twenty-one papers were selected from the literature during the period 2000-2016, which were done in different regions with 10 different methodologies. The studies were systematically reviewed and allowed 50 observations. Validation methods were conducted to surpass bias. The findings obtained may be of interest to railway managers and public agencies that control and regulate railway systems.

The results suggest that railways located in Japan and in the US have characteristics that push them toward increasing efficiency. Factors such as productivity in the Japanese case and ATDF in the American case may explain the outcome and can lead to further investigations. Railway systems that transport passengers reached a significantly higher efficiency than that of conventional cargo systems. Furthermore, findings suggest that the ability of the railway systems to combine passenger transportation with their more complex systems and procedures of signalling, control & safety, and cargo transport, as in the high productivity Asian (e.g. China) and European (e.g. France and Germany) systems, may mean conditions of improvement in the allocation of resources and greater efficiency. This would imply in an important warning mainly for the American systems, especially those in Brazil and US, where there is a predominance or almost exclusive cargo transportation. The way the efficiency frontier study is conducted including methodology, NVAR, and the ratio between NDMUs and NVAR may influence the scores. Unexpectedly, database structure did not significantly influence the estimates. Additional studies may confirm these effects.

The use of meta-analysis in an economic production sector involves a considerable planning and can face limitations. First, the selection of papers and common variables. The preliminary stages of meta-analyses such as the review of the literature and the selection of the studies and variables are much more complicated than in quantitative reviews that have been completed so far (MAKSIMOVIĆ, 2011). Besides, papers do not always express variables, estimates, standard errors, etc. the same way. Sometimes part of the information is omitted, leading the meta analyst to face difficulties or even a limitation. This is the case of this research. Second is that, although meta-analysis has led to a great progress in quantitative researches (MAKSIMOVIĆ, 2011), findings can be limited by the selection criteria of papers in the literature. Because of this, complementary studies should be conducted including the enlargement of the literature review. Third, a valid meta-analysis depends on accessory robustness analysis such as independence of terms, independence of observations, the requirement of normal distribution of the dependent variable, and other potential resources of misleading results when in the presence of heterogeneity, few number of studies or covariates (HIGGINS; THOMPSON, 2004). This research, besides the findings reached, tried to conduct a robust meta-analysis in an economic sector in a way that it can be replicated. That could be a proper finding of the research.

The study has as a limiting factor the lack of the value of the standard error and yearly estimates, as this information is not always available. Further studies can be conducted such as the statistical significance of the effect of regulatory variables (existence of barriers to entry such as discriminatory access tariffs or difficulty in allocating slots to third parties) and of the ownership of the railways. All of them are important contributions to the advancement in the study of efficiency frontiers in the railway sector.[1]

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3.7 APPENDIX A

Table 3.6:
Railway infrastructure and indicators.

region/country	extension (km)	%	passengers.km (million)	%	tons (millions)	%	tons.km (millions)	%
Europe	258,270	29%	463,325	16%	1,311	14%	529,112	6%
Russia	85,262	9%	120,413	4%	1,329	14%	2,304,758	26%
Africa	55,600	6%	62,830	2%	82	1%	136,492	2%
Americas	269,155	30%	27,531	1%	2,201	24%	2,856,306	32%
Asia & Oceania	232,714	26%	2,278,880	77%	4,265	46%	3,073,072	35%
Total	901,001	100%	2,952,979	100%	9,188	100%	8,899,740	100%

Source: UIC (UIC, 2015) and CIA (CIA, [s.d.]), completed by the authors. Year base: 2015.

Table 3.7:
HSR systems.

region/country	main operator	Indicators			
		length (km)	traffic intensity (billion passengers.km)	productivity (billion passengers.km per 1,000 km)	density (km per 1,000 km^2)
EU (+UK)	--	8,269	114.63	13.9	1.8
France	SNCF	2,142	52.90	24.7	3.9
Germany	DB AG	1,475	24.32	16.5	4.1
Italy	Trenitalia	923	12.80	13.9	3.1
Spain	Renfe	2,871	11.84	4.1	5.7
Others in EU	--	858	12.77	14.9	0.3
Asia	--	26,369	368.17	14.0	0.6
China	CR	21,688	254.88	11.8	2.3
Japan	JR group	3,041	89.17	29.3	8.2
South Korea	Korail	598	14.88	24.9	6.0
Taiwan	THSR	354	9.24	26.1	9.8
Others	--	362	0.01	0.0	--
Total	--	35,000	482.81	13.8	--

Source: UIC (UIC, [s.d.]), completed by the authors. Year base: 2015
SNCF=Société Nationale des Chemins de fer Français; DB=Deustch Bahn; Renfe=Red Nacional de los Ferrocarriles; CR=Chinese Railways; JR=Japanese Railways; Korail= Korea Railroad Corporation; THSR=Taiwan High Speed Rail.

4. 3RD PAPER: “EFFICIENCY OF THE RAIL SECTIONS IN BRAZILIAN RAILWAY SYSTEM, USING TOPSIS AND A GENETIC ALGORITHM TO ANALYSE OPTIMIZED SCENARIOS”

“EFFICIENCY OF THE RAIL SECTIONS IN BRAZILIAN RAILWAY SYSTEM, USING TOPSIS AND A GENETIC ALGORITHM TO ANALYSE OPTIMIZED SCENARIOS”

Abstract

A railway system plays a significant role in countries with large territorial dimensions by providing inputs and goods in a more cost effective and sustainable way. The Brazilian rail cargo system (BRCS), however, presents a heterogeneous performance and is focused on the transportation of mineral and agricultural bulk for export with a low average efficiency, reducing its economic impact. The paper investigates the extreme performances of BRCS through a new hybrid model that combines the methodology Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) with a genetic algorithm of differential evolution for estimating the weights of the criteria in optimized scenarios, which is a gap in the literature. In a second stage, the significance of the selected variables was evaluated. The transport of any type of cargo, the centralized control of the operation, and the sharing of the railway track are significant for the scores. The findings suggest that competition and diversification of services are key elements for high performance. Public and management strategies are discussed.

Keywords: TOPSIS; genetic algorithm; efficiency; railway sections; railroads; Brazil

4.1 INTRODUCTION

The Brazilian rail cargo system (BRCS) has an extension of about 29,000 km deployed since the second half of the 19th century in a dispersed and isolated way (MUNHOZ, [s.d.]) where modern and obsolete infrastructure of the railway track and rolling stock can be found side by side. It is operated by private capital railway concessionaires broken down into subsystems, granted by the federal government between 1996-1999. The concession model included, cumulatively, the granting of the right to use the railway along with the lease of the operational assets and the support facilities required for the operation.

The concession term in most cases was for 30 years. The BRCS subsystems is translated into a regional sector and verticalized monopoly (MARCHETTI; FERREIRA, 2012) with low inter-modal competition, even though there are regulations that seek to promote the increase of supply and competition on the network by means of the trackage right regime, where the access to the infrastructure of another concessionaire with its own trains is done in exchange for a fee, or the haulage right regime, where the owner of the railroad operates trains for another concessionaire in exchange for a fee (ANTT, 2011; LAURINO et al., 2015).

The BRCS is heterogeneous, presenting different standards of efficiency among the operators, and distinct physical and operational characteristics (MARCHETTI; WANKE, 2017). The main cargo on the tracks are mineral and agricultural commodities for export with a low diversification of scope, reaching up to 95% of its offer (EPL, 2016). It includes different track gauges: metric (1.0 m), broad (1.6 m), and mixed. The subsystems are installed in all regions of the country, but with low connectivity and integration among them. There are railway sections with high daily circulation of trains and low idleness, but many stretches are little used or no used at all, due to the sinuous and extended geometry of the track or even shortage of supply or demand. The technology of the operation comprises elements cuch as computers embedded in the locomotives, centralized control of the operation, auxiliary power along critical stretches, and the ability to transport hazardous materials. Its average speed is slow (ANTT, 2013; MARCHETTI; FERREIRA, 2012), which inhibits access to cargo of higher added value.

Brazil has a cargo transportation modal network that is unbalanced when compared with countries of large territorial dimensions (EPL, 2016). The insertion of rail transport is low (15%) while road transport is the highest with a 65% market share, including long distances trips. This is where the greatest economic, transportation, and environmental costs are concentrated. Public policies should attempt to change this reality in the long term in order to rebalance the Brazilian transportation network, reducing the transportation and logistics costs, and the emission of pollutants produced from burning fuels in the transport sector in Brazil, which is twice of the transport average emission registered in the world (FERREIRA et al., 2016).

As the BRCS has a heterogeneous performance focused on bulk for export presenting low average efficiency and an economic impact lower than expected, the questions of this research are as follows: How can a high performance scenario be achieved in the BRCS? What are the significant characteristics of the high performance scenario in the BRCS?

The performance of the railway sections, which are the stretches between rail yards, was analysed to answer the research questions. The availability of a database with information of the physical and operational characteristics, transportation capacity, idleness, and the type of the regulation of the railway sections of each concessionaire network enabled innovative conclusions about the entire BRCS's performance, which would not have been found with the traditional analysis of aggregate data. There were 7,351 railway sections selected from 2013 to 2016. The database comes from the Network Statement drawn up every year by the concessionaires and disclosed by the National Land Transportation Agency (ANTT, 2018).

The paper evaluates the efficiency of rail sections by using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) that combined with a Differential Evolution Optimization genetic algorithm, simulates the optimized behaviour of the scores in BRCS' low and high performance scenarios.

The methodology proposed differs from studies already done in the literature. Several articles have already used a hybrid methodology for analysis of alternatives by using some genetic algorithm for a multi-objective optimization followed by TOPSIS for ranking solutions, in different areas of application, as indicated in Section 4.2. However, using a genetic algorithm of differential evolution for identifying the weights to be assigned to the variables (criteria) selected in the TOPSIS model for building optimized scenarios was an innovation. As to the best of our knowledge, a simulation of the extreme scenarios in a (railway) system based on the characteristics of its network subparts (the rail sections) using a genetic algorithm to optimize the performance of the entire system according to the TOPSIS scores of the subparts is an innovative contribution of this research.

The determinants of BRCS's performance are revealed in the second stage and are additional contributions from the research. By using a Tobit model, the significance of the contextual variables selected in each scenario was analysed such as the technologies employed in the railroad operation, the type of cargo transported, and the type of regulations regarding the use of the railway track (restrictive or open), among others. The significant attributes of scenarios of low and high performance were highlighted. By analysing the score percentiles, the profile of the railway of each concessionaire was identified in the extreme deciles. The less efficient and most efficient railway sections of each scenario can be identified, offering an important contribution of an administrative and managerial nature.

The methodology proposed can be applied to different economic sectors treated as a network such as passenger and cargo railway systems and energy or telecommunication transmission lines.

The remainder of this paper is organized as follows. Section 4.2 presents the literature review and indicates the gap found. Section 4.3 describes the methodology used to analyse the data. The data are presented, and the results are discussed in Section 4.4. Public policies to achieve a high performance scenario are discussed, as well as management possible insights due to the availability of the ranking of the concessionaires' railway sections per scenario. Section 4.5 concludes the discussion and shows the limitations of the research while giving suggestions for new studies for going deeper into BRCS's efficiency frontier.

4.2 LITERATURE REVIEW

The objectives of the literature review were twofold. The first objective was to list the applications where there was a selection of multi-criteria alternatives with the use of TOPSIS in infrastructure, transport, and more specifically in the railway sector. The second more comprehensive objective was to identify the articles that used some genetic algorithm to solve multi-optimization problems together with the TOPSIS methodology, including different areas of interest. The strategy was to investigate how these methods, widely employed in studies that transcend the infrastructure, transport, and the railway sectors, were combined in the literature, concluding whether there is an innovative application in the present study A comprehensive survey of the literature involved articles in English reviewed by peers on the basis of widely recognized data.

4.2.1 TOPSIS in Infrastructure, Transport, and the Railway Sector

Several authors have used the TOPSIS methodology as a multi-criteria method for making decisions on the ranking of infrastructure alternatives in their studies, whether alone or in combination with other methods. The uncertainty as to the weights of the criteria was treated in different ways. The main methods to determine the weights of the selection criteria include Shannon Entropy, Analytic Hierarchy Process (AHP), Fuzzy AHP, and Delphi Survey. Other authors have used the Fuzzy-TOPSIS method for judging the relevance of the criteria, treat the uncertainty, and ranking the alternatives.

Askarifar, Motaffef and Aazaami (2018) ranked the necessary public infrastructure requirements along the Mokran coast in Iran with Best Worst Method and TOPSIS to determine the priorities. The results show that ports and private terminals are the best choices for investment while security infrastructure, transport, and energy should be the public administration priorities. Keshavarz-Ghorabaee et al. (2018) proposed a conceptual bridge design process under uncertainty by applying a modified Fuzzy TOPSIS method and compared the results with other multiple criteria decision making (MCDM) methods, concluding that the results were valid. Kannan, Pokharel and Kumar (2009) interpret the 15 alternatives for choosing a third-party reverse logistics provider (3PRLP) in India using Interpretive Structural Modelling (ISM) and Fuzzy-TOPSIS, arriving at a decision-making tool for choosing an 3PRLP. Afful-Dadzie et al. (2015) applied Fuzzy TOPSIS to create a framework for selecting states for aid facilities. Farajpour and Yousefli (2018) identified the parameters that influence the flow of information in supply chain prioritized towards three criteria (measurability, being illustrative, and parameters relevancy) and applied a Fuzzy TOPSIS method to rank the parameters. They concluded that supply chain hardware, and infrastructure; information software, sharing timeliness, and recency, and organizational rewards are the highest priorities, while internal and inter-personal communications, and users' trust, and tendency stand at the bottom of the ranking. Liu and Wei (2018) explored risk factors through a survey and calculated the overall risk levels of public-private partnership (PPP) projects for electric vehicle (EV) charging infrastructure with an integrated Fuzzy TOPSIS, ranking the alternative projects. Rahdar and Khalily-Dermany (2017) proposed an optimization model for time-resource allocation in wireless ad-hoc networks applying Fuzzy TOPSIS to assign more appropriate time-slot to nodes, reaching the conclusion that the algorithm proposed is more efficient than the available ones. Onat et al. (2016) used a Fuzzy MCDM and TOPSIS method to rank the life cycle sustainability performance of alternative passenger vehicles. The results indicate that hybrid and plug-in hybrid EVs are the best alternatives for both Scenario 1 (existing electric power infrastructure in the US) and Scenario 2 (the electricity to power EVs is generated exclusively via solar stations).

Applying a hybrid of the Fuzzy Delphi and TOPSIS methods, Pham, Ma and Yeo (2017) developed a methodology to choose the locations of logistics centres. According the authors, the most important factors are demand, closeness to market, production area, customers, and transportation costs and the provinces of Ho Chi Minh City were the best location for logistics centres in Vietnam. Jayasooriaya et al. (2018) applied a Delphi survey and TOPSIS to optimize green infrastructure treatment train configuration and the sizing combinations for stormwater management in industrial areas. The authors used a Delphi survey to identify the environmental, economic, and social performance measurements and to obtain the weights. The TOPSIS method was used to identify the optimum from 10 alternatives.

Huang et al. (2018), with a focus on identifying the level of third-party logistics service sites based on the Chinese railway stations, applied a two-stage model combining EWM based on Shannon entropy and TOPSIS and concluded that the eight first-class railway logistic bases are Beijing, Harbin, Xi'an, Wuhan, Nanjing, Guangzhou, Chongqing, and Taiyuan. Other 28 cities were selected as the second-class railway logistic centres. Zhang et al. (2018) applied the structural Entropy-TOPSIS model to evaluate the performance of a public transport priority implementation in the city of Wuhan from 2006 to 2015, reaching the conclusion that the performance improved from poor to excellent. The weights were determined according to the EWM. Baghery, Shojaei and Khorami (2018) investigated the conditions of the tourism infrastructure from different provinces of Iran and used the Vikor and TOPSIS methods to rank the cities according to the indicators selected. They used the Shannon Entropy method to determine the weights of the indicators. The authors reached the conclusion that the Province of Tehran is under the best conditions and that the province of Ilam is under the worst conditions.

Some authors used AHP to determine the weights of the selection criteria and combined with TOPSIS to rank the alternatives. Moosivand and Farahani (2013) combined AHP and TOPSIS models to determine the factors attracting tourist in the Isfahan province (Iran) and rank the cities, reaching the conclusion that Isfahan and Kashan are the top two tourist destinations in the province. Singh, Gunasekaran and Kumar (2018) used a Fuzzy

AHP to determine the relative weights of the different criteria shortlisted and a Fuzzy TOPSIS to rank the third-party logistics (3PL) for a cold chain and to select the best 3PL based on performance. The major reasons behind the top ranking are an emphasis on automation, innovation, tracking and tracing, and flexibility. Fabianowsky and Jakiel (2018) used an innovative integrated calculation algorithm that uses the modified extent analysis method on the Fuzzy AHP (EA FAHP) method to obtain the weight vector of the criteria and the Fuzzy TOPSIS to reflect the actual assessment processes of the technical condition of railway culverts. Zhang and Xu (2009) used AHP to evaluate weight criteria and an extension TOPSIS with triangle fuzzy numbers to determine the optimal choice in building or rebuilding projects of urban railway passenger stations. Yurdakul and Iç (2005) developed a performance measurement model (PMM) to obtain an overall performance score of a manufacturing company in its operational activities. The AHP approach was used to weigh the dimensions and their sub-components combined with TOPSIS. PPM can be used to detect a company's weak areas in which rating scores are lower than the industry average. Amiri et al. (2009) presented a hybrid MCDM model to assess the competence of the firms using fuzzy sets to measure the performance, AHP to evaluate the weights, and TOPSIS to rank the firms, considering different values of α-cut, and a linear assignment method to obtain final rank for alternatives. They concluded that the model is practical for analysing MCDM alternatives.

Alemi-Ardakani et al. (2016) investigated the effect of weighting methods in TOPSIS and developed a framework to optimize weave pattern selection in fibre reinforced polymer composites. Different types of weighting methods were compared: entropy, the modified digital logic (MDL), the criteria importance through inter-criteria correlation (CRITIC), the Numeric Logic (NL), and the Adjustable Mean Bars (AMB) methods. The authors concluded that, the NL method, compared to the MDL, increased the accuracy of weights for an expert decision maker (DM), and the AMB method is more interactive, and visual for a less experienced DM. A combinative weighting method was presented.

Behzadian et al. (2012) identified that TOPSIS works satisfactorily across different application areas, and then conducted a literature survey on TOPSIS applications and methodologies, containing 266 papers from 103 journals since 2000, separated into diverse areas including Supply Chain Management and Logistics. Finally, applying a different approach, Liu, Wang and Wang (2017) used an Improved Analytic Hierarchy Process (IAHP) and Entropy Weight Method (EWM) to calculate the weights and a cloud model to overcome the problem of fuzziness and randomness in emergency railway decision-making.

4.2.2 The Applications of a Genetic Algorithm together with TOPSIS

Other studies used genetic algorithms for solving multi-objective optimization problems especially together with TOPSIS for ranking the alternatives. The interest of the research was to recognize the way that these methods were combined in the literature in different areas of interest, concluding for an innovative application in the present study.

Cheng, Ye and Yang (2009) applied the non-dominated sorting genetic algorithm (NSGA-II) to solve optimization functions and the TOPSIS approach to identify the best solution from a Pareto optimal solution set. They reached the conclusions that the NSGA-II outperforms the other genetic algorithms to help manufacturers to find an appropriate collaborative manufacturing chain for the manufacturing of complex products. Azadeh, Kor and Hatefi (2011) created a hybrid genetic algorithm and TOPSIS simulation (HGTS) for determining the most efficient number of operators and labour assignment in cellular manufacturing systems. The entropy method was used to estimate the weight of the attributes. The authors concluded for the superiority and advantages of the proposed HGTS over TOPSIS, Data Envelopment Analysis (DEA), and Principal Component Analysis (PCA). Azzam and Mousa (2007) applied a combination of a genetic algorithm and the ϵ-dominance concept to solve the multi-objective reactive power compensation problem and used TOPSIS to assess the best solution from a set of alternatives. The results demonstrate the capabilities of the technique proposed in a single run. Cheng et al. (2006) presented a general framework to the multiple criteria parameter calibration problem, combining a genetic algorithm with TOPSIS for a rainfall-runoff model for flood forecasting in China. TOPSIS gave the ranking order of alternatives (chromosomes) and the attributes of multiple criteria are the flood characteristics. They concluded that the hybrid method is and easier when compared with previous studies and feasible and robust to be applied in practice. Huang and Tang (2005) adopted the Taguchi method, neural networks, TOPSIS, and the genetic algorithm to develop an optimization system that evaluates, simultaneously, four qualities of as-spun polypropylene yarn, rather than using engineering experience. The performance of the parameters was assessed with TOPSIS while the parameter measurements and the parameter combination were optimized with the genetic algorithm. The authors showed that algorithm could obtain the smallest denier, and breaking elongation, the second smallest denier variance, and the largest tenacity. Taleizadeh, Niaki and Aryanezhad (2009) used a hybrid method of Pareto, TOPSIS, and genetic algorithm to solve multi-periodic inventory control problems. Olçer (2008) employed a two-stage hybrid approach for solving a multi-objective combinatorial optimisation (MOCO) problem in ship design. In the first stage, through an evolutionary process, a genetic algorithm was used (Frontier) to determine the set of pareto-optimal solutions. TOPSIS was adopted to rank these solutions in the second stage. The author concluded that the model can be applied in various MOCO problems in ship design and shipping. Goyal, Jain and Jain (2012) applied a NSGA-II to identify the pareto frontiers for machine selection based on machine reconfigurability and operational capability along with the cost. Shannon entropy weighted the attributes and TOPSIS are employed to rank the pareto frontiers. The study reveals that the hybrid approach has a great potential in handling the reconfigurable manufacturing systems optimisation. Li et al. (2008) presents an integrated methodology for design and optimization of a chemical process based on the green chemical principles. They performed a multi-objective mixed integer non-linear mathematical model, considering environmental and economic factors, solved by a NSGA-II. TOPSIS was used for identifying the set of optimal parameters. Dhanalakshimi et al. (2011) applied a modified NSGA-II (MNSGA-II) to solve the combined economic and emission dispatch problem with conflicting objective such as fuel cost and emission. TOPSIS was used to decide the best solution. Jeyadevi et al. (2011) compared the performance of a MNSGA-II, NSGA-II, and multi-objective particle swarm optimization (MOPSO) with respect to multi-objective performance measures optimal reactive power dispatch. TOPSIS is applied to determine a best compromise solution. The authors reached the conclusion that the MNSGA-II performs better than NSGA-II.

The gap in the literature was found, after identifying the articles that used TOPSIS in infrastructure and in the railway sector, whether alone or in combination with other methods, and the studies that especially applied TOPSIS together with genetic algorithm in diverse areas. To the best of our knowledge, no study has been developed using a genetic algorithm for determining the weights of the criteria selected in the TOPSIS model in order to build optimized scenarios, which constitutes the gap that the article seeks to fill. The use of railway sections is also an innovation that makes it possible to associate efficiency with the physical and operational characteristics, the transportation capacity, idleness, and the type of regulation of each railway section.

4.3 METHODOLOGY

The methodology proposed uses a genetic algorithm of a differential evolution to change the weights of the criteria (mutation) and to optimize the objective function, the median of the TOPSIS scores of the railway sections, simulating virtual optimized scenarios of low and high performance whose characteristics will be evidenced by a Tobit model. The methods are presented below.

4.3.1 TOPSIS

The *Technique for Order Preference by Similarity to Ideal Solution* developed by Hwang and Yoon (1981) is a multi-criteria decision analysis (MCDA) technique based upon the concept that the alternative chosen should have simultaneously the shortest distance to a (positive) ideal solution (A^+) and the farthest distance from a negative ideal solution (A^-). The ideal solution maximizes the benefit and also minimizes the total cost, and the negative-ideal solution minimizes the benefit and also maximizes the total cost (AZADEH; KOR; HATEFI, 2011). The TOPSIS method meadures the weighted Euclidian distances, as showed in Figure 4.1.

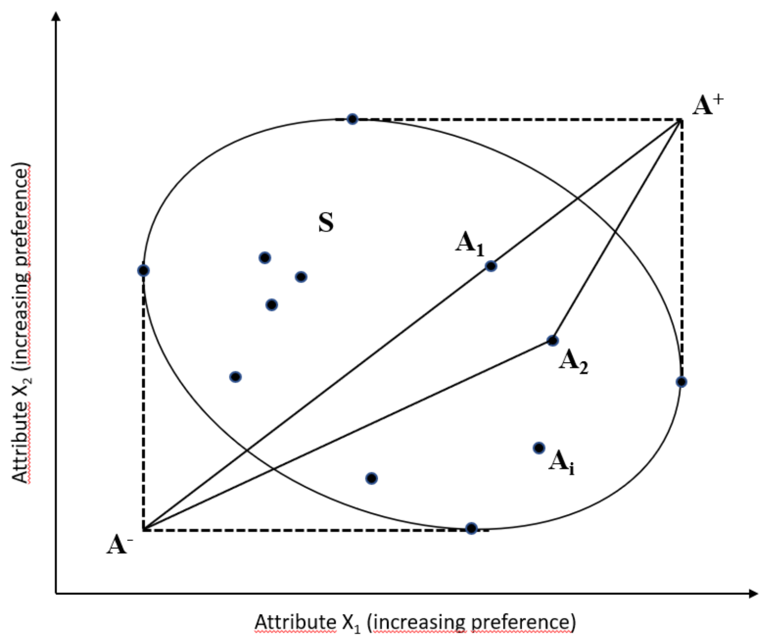

Figure 4.1: Euclidean distances to the ideal and negative-ideal solutions

Source: Hwang and Yoon (1981)

The TOPSIS analysis starts with normalizing the decision matrix that can reduce the computational problems that can occur due to different units and measurements of the criteria selected (JAYASOORIYA et al., 2018). The successive steps present the TOPSIS method.

Step 1 is to construct the normalized decision matrix (NDM), which element r_{ij} is calculated by:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \qquad (1)$$

where x_{ij} = outcome of i^{th} alternative (m) with respect to the j^{th} criterion (n).

Step 2 is to multiply the columns of the NDM by the associated weights (w_j), finding the weighted and normalized decision matrix with the v_{ij} components.

$$(v_{ij})_{mxn} = (w_j . r_{ij})_{mxn} \qquad (2)$$

Step 3 is to determine the ideal solution [A^+], which is the best performance in each positive and negative criteria (the perfect alternative), and negative ideal solution [A^-].

$A^{+} = \{(\max_i \; v_{ij} \mid j \in J), (\min_i \; v_{ij} \mid j \in J') \mid i = 1, 2, \dots, m\} = \{v_1^{+}, v_2^{+},$
$\dots, v_j^{+}, \dots, v_n^{+}\}$ (3)

$A^{-} = \{(\min_i \; v_{ij} \mid j \in J), (\max_i \; v_{ij} \mid j \in J') \mid i = 1, 2, \dots, m\} = \{v_1^{-}, v_2^{-},$
$\dots, v_j^{-}, \dots, v_n^{-}\}$ (4)

where J = {j = 1, 2, ..., n | j, associated with benefit criteria} and

J´ = {j = 1, 2, ..., n | j, associated with cost criteria}.

Step 4 is to calculate the Euclidean distance for vectors [A+] and [A-] for each component of the sample from the ideal alternative (v_j^{+}) and from the non-ideal alternative (v_j^{-}), saving [d_i^{+}] and [d_i^{-}], where:

$$d_i^{+} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^{+})^2}, \quad i = 1, 2, \dots, m; 0 < d_i^{+} < 1 \tag{5}$$

$$d_i^{-} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^{-})^2}, \quad i = 1, 2, \dots, m; 0 < d_i^{-} < 1 \tag{6}$$

Step 5 is to calculate the relative closeness of a particular alternative (A_i) to an ideal solution [ξ], where:

$$\xi = \frac{d_i^{-}}{(d_i^{+} + d_i^{-})} \; ; 0 < \xi < 1 \tag{7}$$

Step 6 is to rank the alternatives by the highest scores [ξ].

In the TOPSIS method, the relative importance of each criteria is exogenously defined, which is different from other non-parametric MCDM models that determine performance levels of units. Although computationally simple and with no constraints as to the number of criteria, determining the weights can be an issue for the researcher (Aye et al., 2017). Besides, the TOPSIS method does not offer details about the determinants of the scores. To solve these issues, a genetic algorithm was applied to determine the weights considering the optimized objective function, thus building two extreme scenarios. In a second stage approach, the Tobit regression revealed the determinants of the scores according to the different optimal scenarios found.

4.3.2 Genetic Algorithm

The genetic algorithm (GA) is one of the optimization algorithms, usually called evolutionary algorithms (EA), created by Holland (1975) in the 1960s inspired by the process of natural selection. It is commonly used to generate high quality solutions for global and combinatorial optimization by bio-inspired logical operators. The solution (chromosome) is repeatedly evolved until the best solution is attained. The GA creates a population of solutions and applies genetic operators (mutation and crossover) to evolve the solutions in order to find the best one(s) (AZADEH; KOR; HATEFI, 2011).

In the 1990s, Storn and Price (1997) developed the evolution strategy named differential evolution (DE). The DE algorithm is particularly well-suited to find the global optimum of a real-valued function in a wide variety of fields, including operation research. The members of successive generations are more likely to represent the global minimum of the objective function, the optimization process (ARDIA et al., 2011a). The DE algorithm performs well with variables with distinct distributions and demands a considerable but manageable processing time. The implementation of DE using R uses DEoptim package, first published by Ardia, D. in 2005[1] (ARDIA et al., 2016).

Each generation transforms the initial population. DE disturbs the current population members $x_{1,g}$ with a mutant, a trial parameter vector $v_{i,g}$, by choosing randomly three members of the population $x_{r0,g}, x_{r1,g}$ and $x_{r2,g}$, the ones more likely to minimize the given objective function.

$$v_{i,g} = x_{r0,g} + F \cdot (x_{r1,g} - x_{r2,g}), \text{ where} \quad (8)$$

i indexes the vectors that make up the population and g indexes the generation

F is a scale factor, typically less than 1. DEoptim package uses F = 0.8 (ARDIA et al., 2016).

Mutations continue until all population members have been mutated or *rand* > *CR*, where *rand* is the random number from μ (0,1) and *CR* is a crossover probability *CR* ∈ [0,1], the fraction of the parameter values that are copied from the mutant. The objective function value associated with v (children) is calculated. If a trial vector $v_{i,g}$ has equal or lower objective function value than vector $x_{i,g}$, $v_{i,g}$ replaces $x_{i,g}$ in the population, otherwise $x_{i,g}$ remains. The algorithm stops after some set number of generations or after the objective function value has been reduced below some threshold (ARDIA et al., 2011a).

The use of a genetic algorithm to determine the weights of the TOPSIS model, simulating optimized scenarios of a production system based on the performance of its subparts, is an innovative approach of this research. Subsection 4.4.3 presents the pseudo-code with the application of the genetic algorithm.

4.3.3 Tobit Model

The stochastic model proposed by James Tobin (TOBIN, 1958) describes the relationship between a non-negative latent variable and the independent variable (vector). The latent variable y_t is linearly dependent on x_t via a parameter β. The error term u_t captures the random influences on the relationship.

$$y_t = x_t\beta + u_t, \quad \text{if } x_t\beta + u_t > 0 \tag{9}$$

$$y_t = 0, \quad \text{if } x_t\beta + u_t \leq 0 \tag{10}$$

t = 1, 2, …, N $\quad u_t \sim N(0, \sigma^2)$

Where N is the number of observations, y_t is the dependent variable, x_t is the vector of independent variables, β is the vector of unknown coefficients, and u_t is the error term with normal distribution N (0, σ^2).

Because of its left censored characteristic, the Tobit model is well adequate for TOPSIS scores as the dependent variable of the regression. In the second stage, the censored regression is applied to evaluate the sign and significance of the contextual variables on the performance scores and is an additional contribution of this research.

4.4 DATABASE, RESULTS, AND DISCUSSION

4.4.1 Exploratory Analysis

There were 7,351 railway sections selected from 2013 to 2016. The database comes from the Network Statement drawn up every year by BRCS's concessionaires and disclosed by ANTT (ANTT, 2018). The errors (railway sections with a length or installed capacity equal to zero) and the missing data that disqualify the railway section for the purposes of the study (installed capacity, minimum curve radius, ramp, dangerous cargo, embedded equipment, type of traffic control, number of operational days per year, or linked capacity not informed) were excluded. Railway sections with a linked capacity equal to zero were considered to be one hundred percent idle. Table 4.1 presents the descriptive statistics of the quantitative variables that characterize BRCS's railway sections. The positive and negative variables used in the TOPSIS model are highlighted.

Table 4.1:
Data statistics.

Variable	Unit	type	min	median	Mean	max	sd
rail section length	[km]	--	0.11	12.37	15.49	225.00	13.88
predominant gauge	[m]	p	1.00	1.00	--	1.60	0.26
minimum curve radius	[m]	p	0.00	225.00	326.80	5,292.00	350.85
# operational days per year	[days]	p	0.00	365.00	360.70	365.00	26.24
installed capacity	[trains/day]	p	0.70	9.10	15.81	223.20	19.63
linked capacity	[trains/day]	p	0.00	2.50	6.96	72.50	11.36
Idleness	[trains/day]	n	-2.00	5.30	8.85	176.50	11.93
bottleneck	[trains/day]	p	0.00	34.90	39.32	200.00	30.58
linked capacity.rail section length	[trains.km/ day]	p	0.00	36.29	87.01	4,650.75	230.86
increasing ramp tax	[%]	n	0.00	1.00	0.97	10.00	0.81
auxiliary power	[hp]	n	0.00	0.00	525.40	12,202.00	1,944.03
percentage of idleness	[%]	n	-100.00	65.10	60.68	100.00	30.58

p = positive; n = negative; idleness = [installed capacity - linked capacity]; bottleneck = [linked capacity/installed capacity*100]; percentage of idleness = [(1- linked capacity/installed capacity)*100]; # rail sections = 7,351 (2013-2016); negative values for idleness means over utilization of the rail section.

Figures 4.2 and 4.3 show the behaviour of the idleness of the railway sections for each BRCS operator. Figure 4.2 presents the idleness boxplot while Figure 4.3, in a complementary way, represents the profile of the railway network's idleness for each concessionaire, whether small, medium, or high. Railway sections with idleness less than or equal to 10% are considered low idleness, idleness above 10% and less than or equal to 50% are considered medium idleness, and idleness above 50% are considered high idleness. It is easy to observe that the average idleness of the BRCS is high and greater than 60% (Figure 4.2) and the railway sections used the most (low idleness) do not exceed 10% of the length of the network of each concessionaire, except for the concessionaires EFC and MRS (Figure 4.3). The concessionaires with their railway network less than 50% idle are EFC, MN, EFVM, and MRS, which not surprisingly are the most efficient (MARCHETTI AND WANKE, 2017) (Figure 4.3).

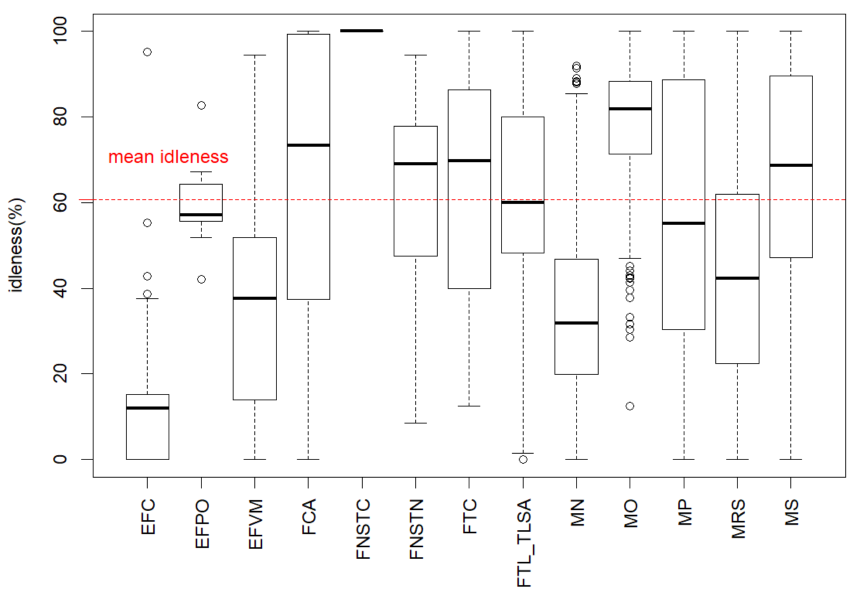

Figure 4.2: Boxplot of rail section idleness by concessionaire

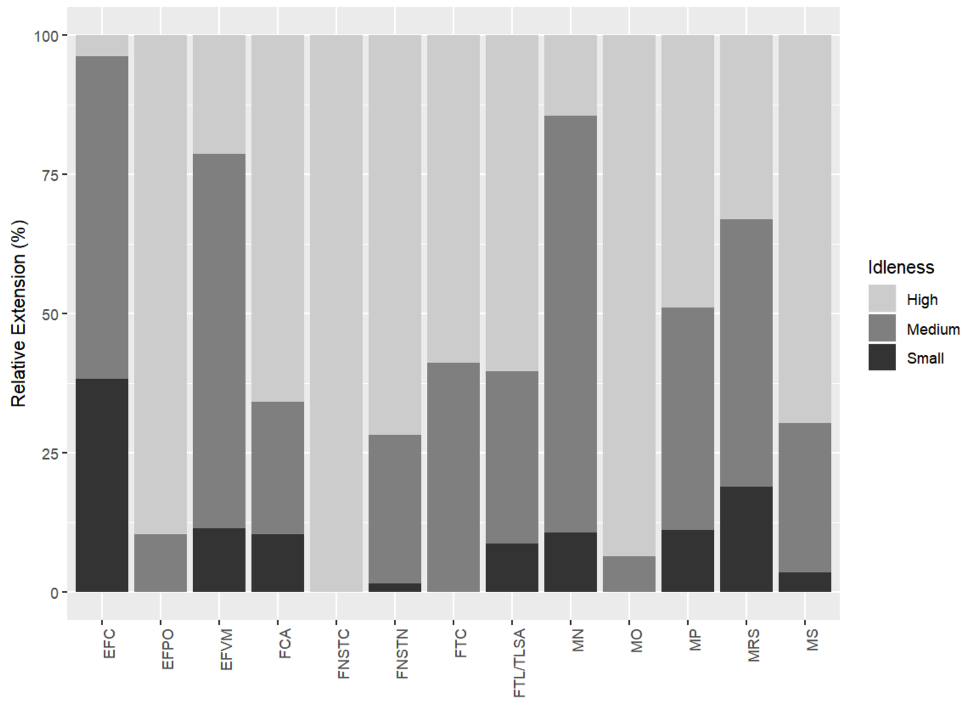

Figure 4.3 – Relative extension of the railway network according to idleness profile by concessionaire

4.4.2 TOPSIS Scores

Positive and negative variables of the TOPSIS model are presented in Table 4.1. When the value of the positive variables increases, it is approaching the ideal solution, and the inverse occurs with the value of the negative variables. Figure 4.4 shows the histogram of the scores of the railway sections obtained from the TOPSIS model considering the positive and negative variables with weights equivalent and equal to 1 (medium scenario). The median of the scores is low (0.38) due to the high idleness of the BRCS.

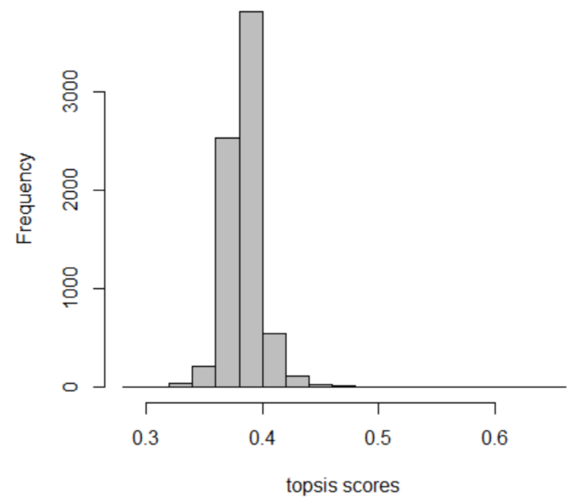

Figure 4.4: Histogram of the TOPSIS scores of the railway sections in the medium performance scenario

The TOPSIS scores of the railway sections in the medium performance scenario were separated by deciles, making it possible to interpret the frequency distribution profile of the sections by concessionaire according to the scores.The first decile is the set of the 10% less efficient railway sections medium scenario qt10) and the last decile is the set of the 10% more efficient railway sections (medium scenario qt90).

Figure 4.5 shows the boxplot and histogram of the TOPSIS scores of the railway sections per concessionaire considering three different situations in the medium performance scenario. On the left, the graph represents the first decile (medium scenario qt 10), the low performers, while on the right the graph represents the last decile (medium scenario qt 90), the high performers, and the integral medium scenario is in the centre. The highest histograms on the left show the largest amount of railway sections with the lowest scores, which are located in concessionaires MO, MP, MRS, and MS. To the right, the concessionaire MRS also holds the highest amount of sections with the best scores, showing heterogeneity. The railway sections of concessionaires EFC and EFVM, the most efficient ones, present the best scores and are concentrated in the last decile, as shown in the medium scenario qt 90 boxplot in the centre.

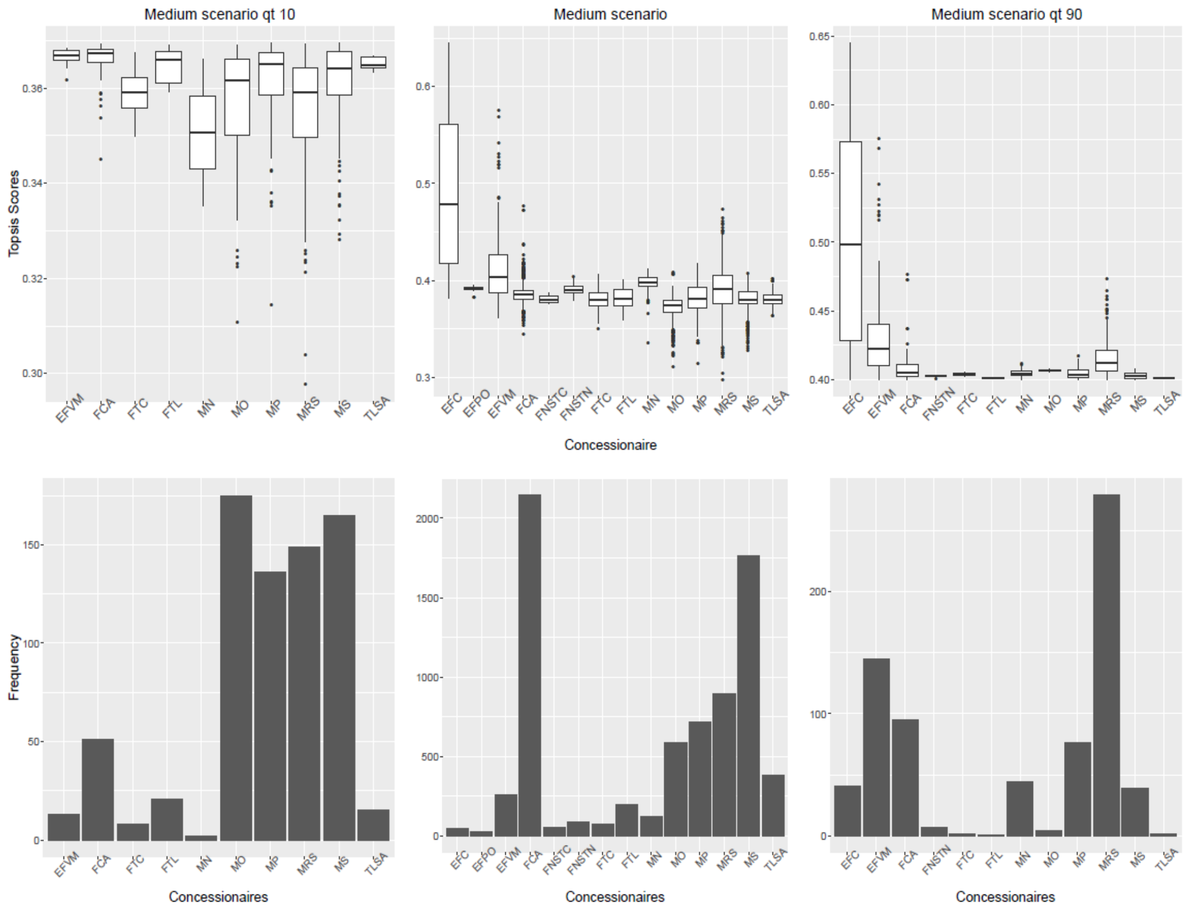

Figure 4.5 – Boxplot and histogram of the TOPSIS scores of the railway sections in three different conditions in the medium performance scenario

4.4.3 Optimization Scenarios

As commented in Section 4.3, a genetic algorithm was used to modify in an evolutionary way the weights applied to each one of the positive and negative variables of the TOPSIS model, creating new generations of values for the scores, and finally, after a limited interaction number, obtaining the optimized scenarios (low and high performance). The objective function is the median of the scores. The reason for using the Differential Evolution Optimization (DEoptim) algorithm (ARDIA et al., 2011a, 2011b) is due to the fact that it works well with variables of different distributions and because its processing time is manageable.

The optimization process took place in accordance with the pseudo code from Table 4.2. First, a random drawing was done, without replacement, of eight railway sections from each concessionaire in order to represent the heterogeneous profile of the BRCS. The sample size was defined considering a population of 7,351 railway sections, a confidence interval of 95%, and an error lower than 10%. Next, the highest and lowest median value of the TOPSIS scores from the sample was determined through a maximization (high performance) and minimization (low performance) process by applying the differential evolution algorithm, saving the vector of weights assigned to the sample's variables. A bootstrapping was implemented, generating 100 new samples. At the end of the processing, the average weights in each scenario were determined. Finally, the TOPSIS scores of the railway section population was calculated considering the optimized weights in the high and low performance scenarios. The objective of building extreme scenarios was to gather evidences that characterize these scenarios, making feasible this way to point out the planning guidelines needed to increase BRCS' efficiency.

Table 4.2:
Pseudo code.

1. Random sort of 8 railway sections per operator without replacement (s = 112, N = 7,351; CI = 95%; error = 10%)
2. Optimize the objective function value with the DE algorithm, considering the high (maximization) and the low (minimization) scenarios for each sort, saving the results (weights)
3. Execute bootstrapping (n = 100)
4. Determine the mean of the weights applied to each positive and negative variable for the high and low scenarios (n = 100)
5. Calculate the TOPSIS scores with the optimized weights for the high and low scenarios considering all railway sections. End of process

s = sample size; N = number of railway sections; CI = confidence interval; n = number of bootstrapping repetitions.

Table 4.3 summarises the optimized weights in the low and high performance scenarios resulting from the optimal solutions found.

Table 4.3:
Weights applied to the TOPSIS variables in the optimized scenarios.

Variable	high scenario	low scenario
predominant gauge	0.20824	0.22204
minimum curve radius	0.02875	0.07779
# operational days per year	1.01578	0.20191
installed capacity	0.01852	0.15048
linked capacity	0.02165	0.24341
idleness	0.16800	0.01491

Table 4.3: Continued.

Variable	high scenario	low scenario
bottleneck	0.05880	0.06297
linked capacity.rail section extension	0.01114	1.82255
increasing ramp tax	0.08802	0.03055
auxiliary power	1.83682	0.01126
percentage of idleness	0.06463	0.08182

Figure 4.6 illustrates the density plot showing the distribution of the TOPSIS scores according to the low, medium, and high performance scenarios. The x-axis shows the score values and the y-axis presents the probability density function (kernel density estimation). One can note that the frequency distribution behaviour of the optimized scores is consistent with the pseudo-code's strategy (Table 4.2).

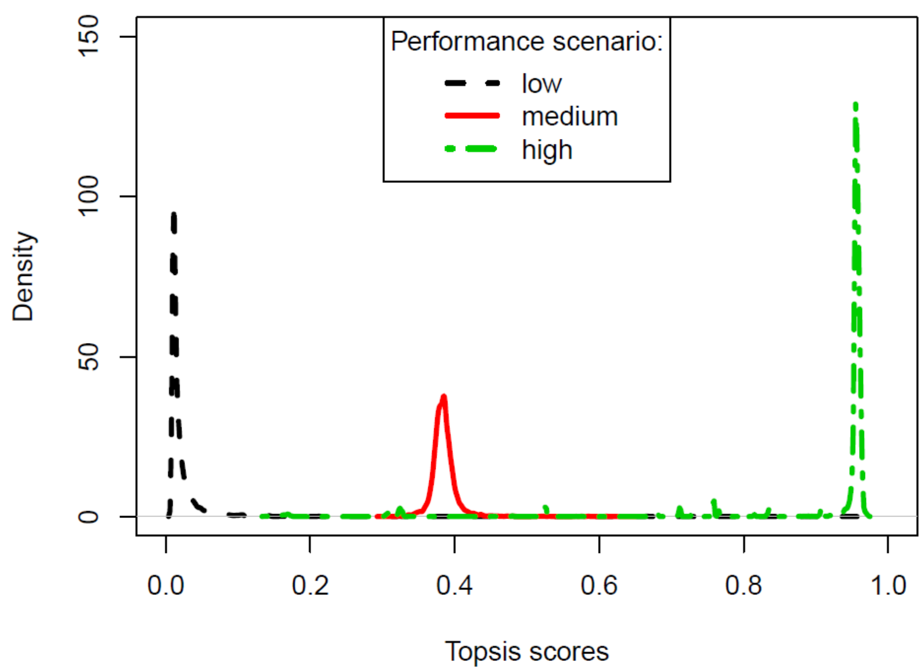

Figure 4.6: TOPSIS score density according to low, medium, and high scenarios

4.4.4 Tobit Model Results

The Tobit model shows the effect of the contextual variables selected on the scores in different scenarios (dependent variable). The independent variables selected were the relative performance of the operators in relation to benchmarking (EFC), the technologies employed in the railroad operation (hazardous cargo, embedded equipment, and track control), the type of cargo transported (agricultural and general cargo), and the type of regulation regarding the use of the railway track (restrictive or open). Table 4.4 presents the results, including coefficient estimates and the significance of the variables according to low, medium, and high performance scenarios. It is worth noting that the transport of all type of cargo, the centralized control of the operation, and the sharing of the rail track are significant for high performance.

Table 4.4:
Tobit regression results.

type of variable	variable	Scenarios					
		Low		Med		High	
		Estimate	signif	estimate	signif	estimate	Signif
	(Intercept)	0.29584	***	0.46931	***	0.99672	***
Brazilian railway operators	EFPO	-0.33434	***	-0.09776	***	0.01007	
	EFVM	-0.23545	***	-0.07398	***	0.02904	
	FCA	-0.33585	***	-0.10265	***	-0.01549	
	FNSTC	-0.33604	***	-0.10588	***	-0.02864	
	FNSTN	-0.32834	***	-0.09727	***	0.00025	
	FTC	-0.32816	***	-0.10291	***	0.01366	
	FTL_TLSA	-0.33214	***	-0.10271	***	-0.06615	**
	MN	-0.30021	***	-0.09137	***	-0.01819	
	MO	-0.33380	***	-0.11197	***	-0.11573	***
	MP	-0.32328	***	-0.10242	***	-0.08669	***
	MRS	-0.29884	***	-0.09276	***	-0.09912	***
	MS	-0.33384	***	-0.10741	***	-0.02187	
diverse characteristics	hazardous_cargo (y=1/n=0)	0.00472	**	0.00243	**	-0.03032	***
	embedded_equipment (y=1/n=0)	0.03971	***	0.00786	***	-0.07184	***
	track_control (CCO=1/local=0)	0.01065	***	0.00614	***	0.01544	*
cargo type	agricultural	0.00138		0.00320	.	0.05397	***
	general_cargo	-0.00382		-0.00172		0.08217	***
legislation	restricted	0.00155		-0.00032		-0.03781	***

signif codes: 0 |***|; 0.001 |**|; 0.01 | * | ; 0.5 | · |; 1 | |
EFC = Estrada de Ferro Carajás S.A; EFPO = Estrada de Ferro Paraná Oeste S.A; EFVM = Estrada de Ferro Vitória a Minas S.A; FCA = Estrada de Ferro Centro-Atlântica S.A.; FNSTC = Ferrovia Norte Sul Tramo Central; FNSTN = Ferrovia Norte Sul Tramo Norte;

Table 4.4: Continued.

FTC = Ferrovia Tereza Cristina S.A.; FTL = Ferrovia Transnordestina Logística S.A.; MN = Rumo Malha Norte S.A.; MO = Rumo Malha Oeste S.A.; MP = Rumo Malha Paulista S.A.; MRS = MRS Logística S.A.; MS = Rumo Malha Sul S.A.; TLSA = Transnordestina Logística S.A.; TLSA (2013-2014), FTL (2015-2016).

Figure 4.7 illustrates the evolution of the behaviour of the coefficients of the Brazilian railway operators, the diverse characteristics employed, the main cargo type transported, and the legislation type according to the low, medium, and high performance scenarios, facilitating the interpretation of the results.

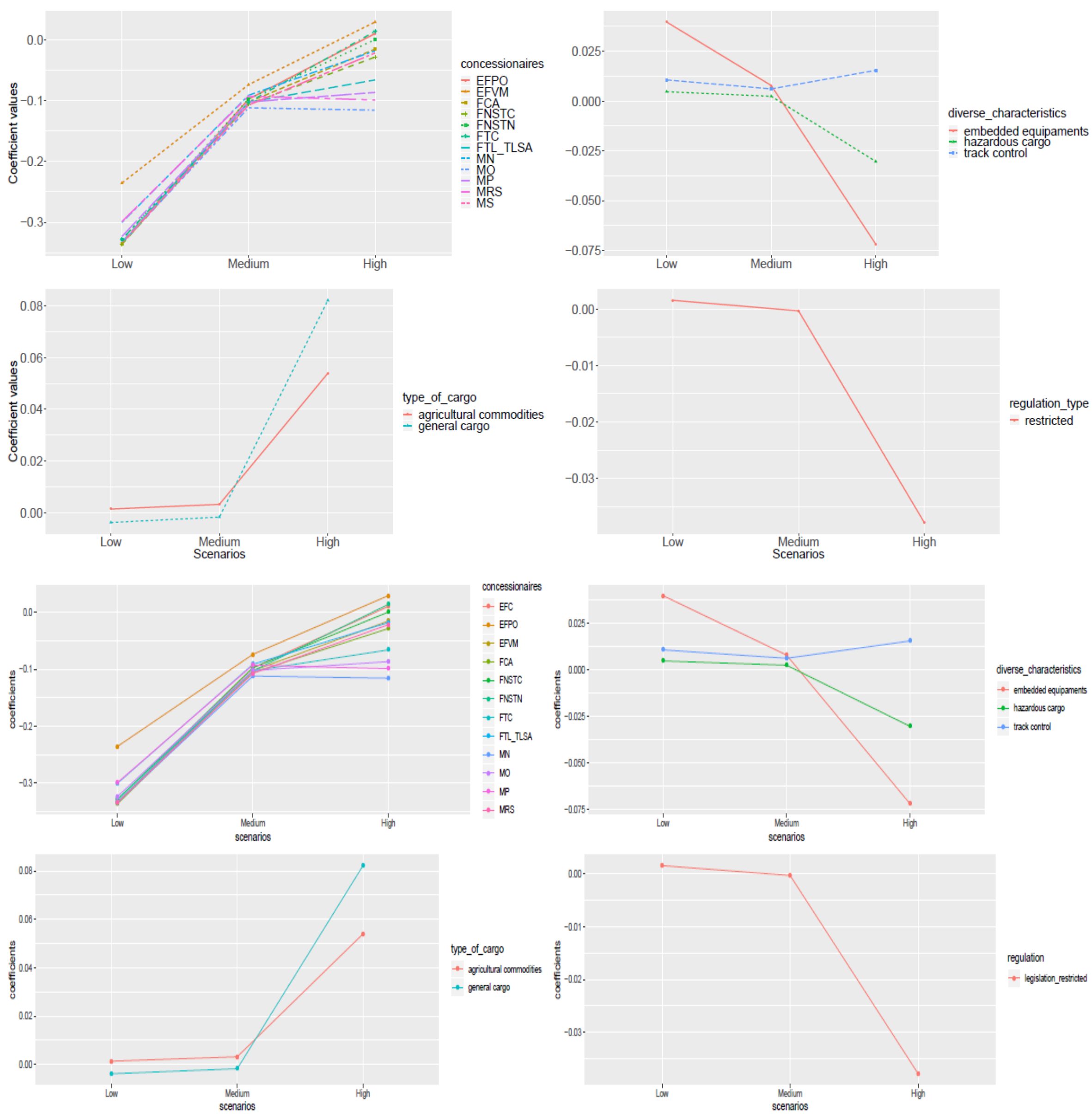

Figure 4.7 – Coefficients behaviour of contextual variables according to the scenario

Considering the upper-left graph of Figure 4.7, one can note that the performance of the concessionaires in low and medium performance scenarios is heterogeneous and significantly distant from the benchmark (negative coefficients). In the high performance scenario, however, there is evolution and convergence in the values of the coefficients showing much less dispersion, indicating improvement in BRCS's overall performance. The concessionaires that transport general and agricultural cargo (EFPO and FNSTN) showed a reversal in their coefficients signal (negative to positive). Considering the upper-right graph of Figure 4.7, one can observe that the use of control centre of operations (CCO), thus bringing more safety to the railway's operation, remained significant in all scenarios, making it the most significant technology to be employed to increase BRCS's efficiency. Considering the lower-left graph of Figure 4.7, one can note that, differently from the low and medium performance scenarios, the transportation of agricultural cargo and general cargo is significant in a high performance scenario. The transport of all types of cargo is significant for high performance. The reversal of the signal found in the coefficients of the concessionaires transporting agricultural and general cargo (EFPO and FNSTN) brings robustness to the evidence. Finally, considering the lower-right graph of Figure 4.7, one can observe that the restrictive regulation presents significantly negative coefficients in the high performance scenario, meaning that the regulations that encourage competition between operators through sharing the use of railway sections (open access) contributes significantly to the scores.

4.4.5 Analysis of the Percentiles of the Optimized Scenarios

The TOPSIS scores of the railway sections in the low and high performance scenarios were separated by deciles, making it possible to interpret the frequency distribution profile of the sections by concessionaire according to the scores. The first decile is the set of the 10% least efficient railway sections (low scenario qt 10 and high scenario qt 10), the low performers, and the last decile is the set of the 10% most efficient railway sections (low scenario qt 90 and high scenario qt 90), the high performers. They assist in understanding the extremes, where the critical railway sections are found, requiring greater attention from administrators for purposes of efficiency gains and possible references.

Figure 4.8 shows the boxplot and the histogram of TOPSIS scores of the railway sections from three different situations considering the low performance scenario.

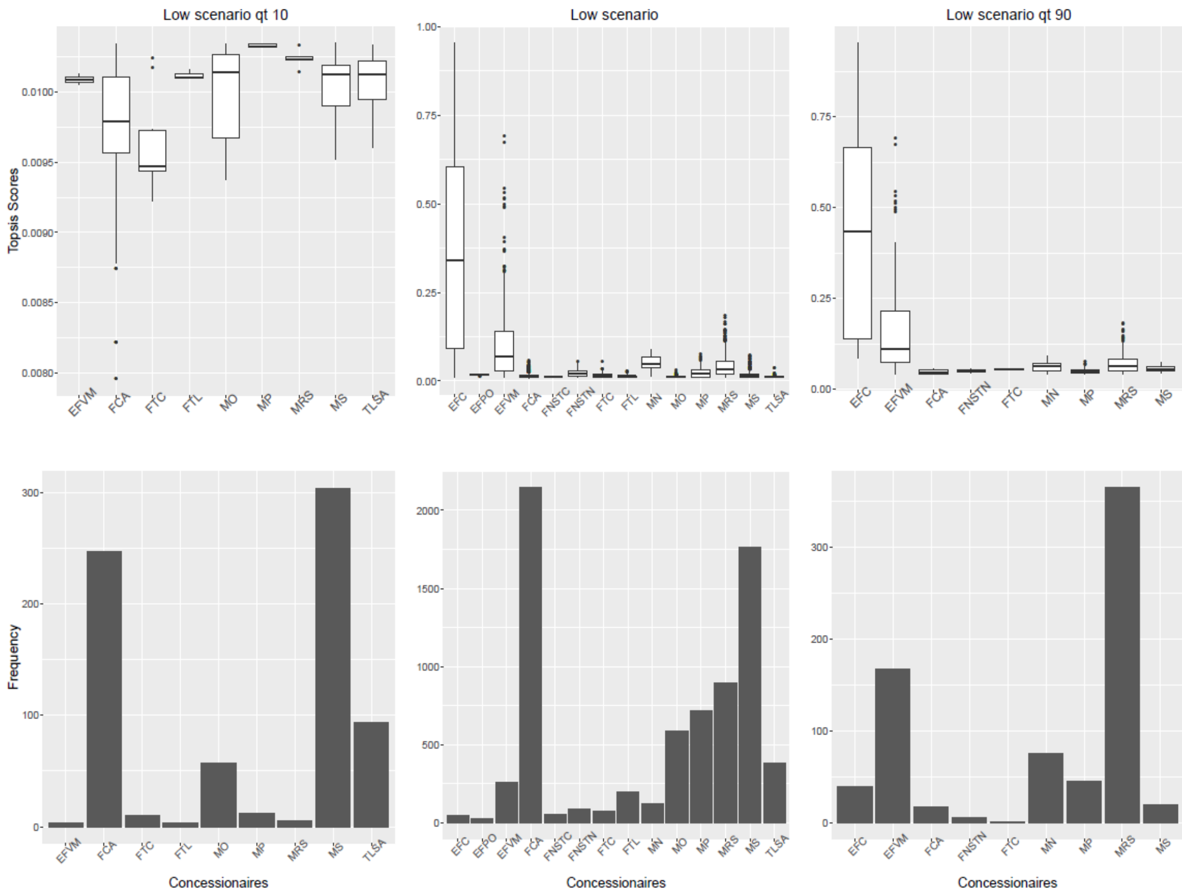

Figure 4.8 – Boxplot and histogram of the TOPSIS scores of the railway sections in three different conditions in the low performance scenario

Some aspects should catch the attention of administrators and those responsible for public policies. On the left, the higher histograms of concessionaires FCA and MS represent the largest quantity of low performing railway sections. To the right, the high histogram of concessionaire MRS represents the largest amount of high performing railway sections. In the centre, considering all the sections, the boxplots of the benchmark concessionaires EFC and EFVM show that they have the railway sections with the highest scores and best operational conditions.

Figure 4.9 plots the same graphs of Figure 4.8, now considering the high performance scenario.

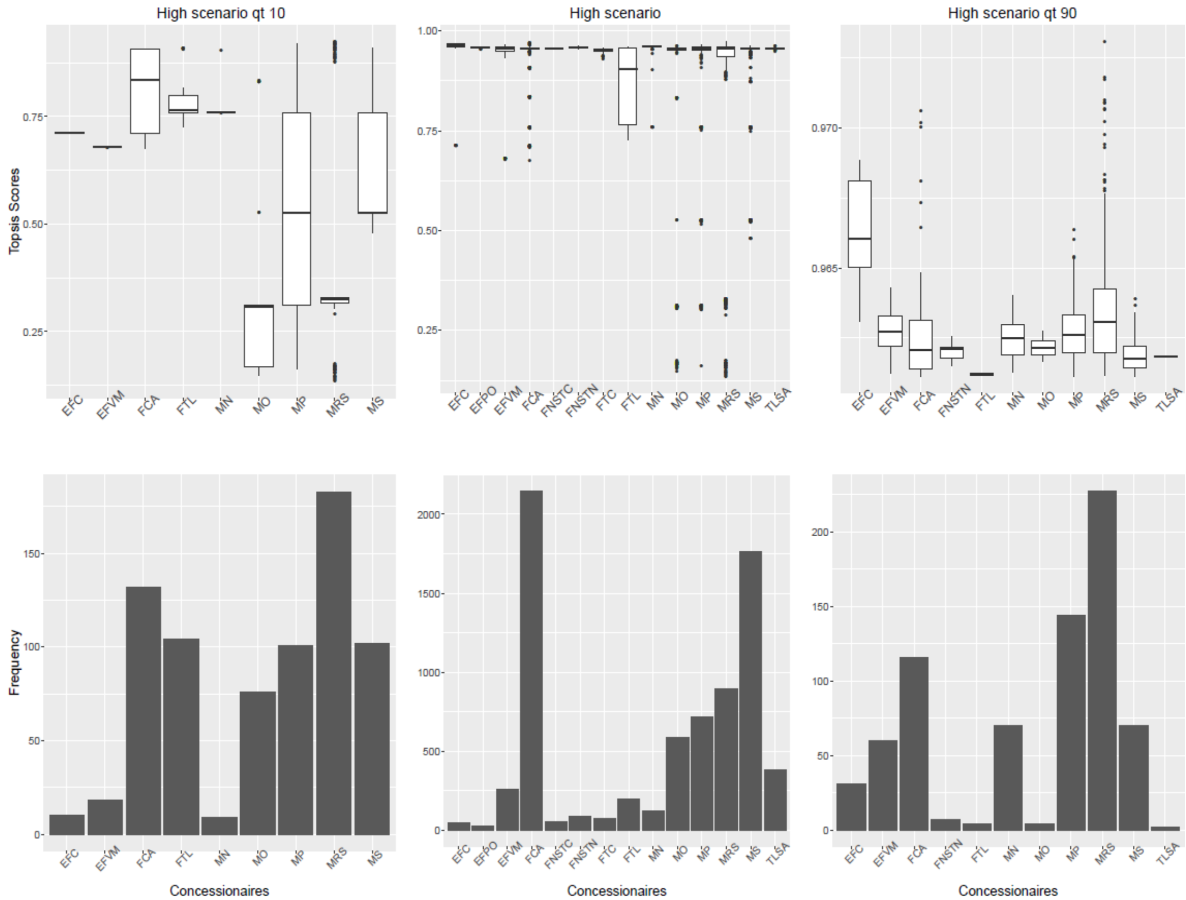

Figure 4.9 – Boxplot and histogram of the TOPSIS scores of the railway sections in three different conditions in the high performance scenario

To the left, the boxplots of concessionaires MO, MRS, MP, and MS show that they hold the lowest performing critical railway sections. On the right, the boxplots of concessionaire EFC and the outlier sections of concessionaires MRS and FCA point out the best railway condition. At the centre, considering all the railway sections, the boxplot of concessionaire FTL shows the worst profile among all operators.

Figure 4.10 shows the scatterplot of the cumulative extension of the railway sections (x-axis) by the number of sections (y-axis) per concessionaire. The heterogeneity (higher dispersion) of the low performance scenario in the first decile (low scenario qt 10) and in the last decile (low scenario qt 90) is replaced by the greater homogeneity (lower dispersion) of the high performance scenario in the first decile (high scenario qt 10) and in the last decile (high scenario qt 90). In the high performance scenario, the performance of the operators is much more homogeneous between the percentiles, confirming the results of the regression.

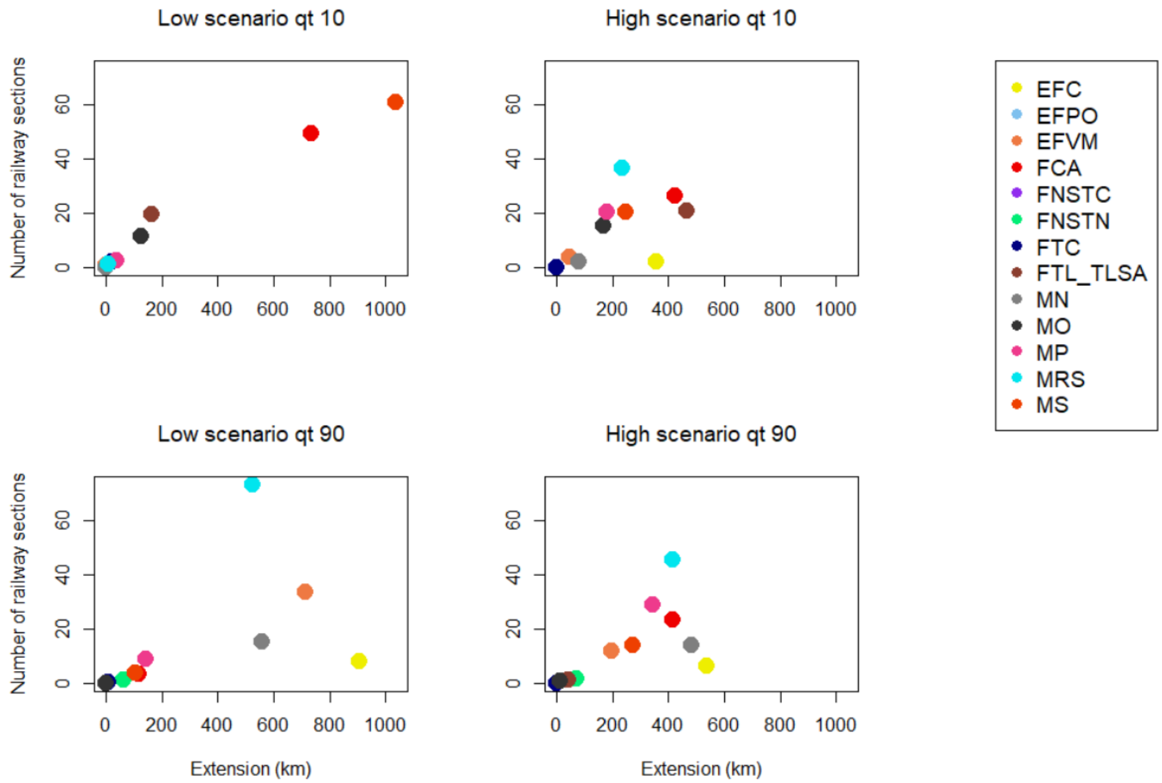

Figure 4.10 – Plot of the number of railway sections vs. cumulative extension (km) per concessionaire, according to the extreme scenarios

4.4.6 Statistical Tests between Scenarios

Table 4.5 provides the results of two statistical tests applied into the variables used in the TOPSIS model (upper part) and one statistical test applied into contextual variables used in the Tobit model (lower part). It shows the statistical results found between the low and high performance scenarios according to low performers (left part) and high performers (right part) quartiles.

The Komolgorov-Smirnov test was used (two sample K-S test) to compare the distribution found in the median of the (positive and negative) variables used in the TOPSIS model between the low and high performance scenarios according to the low and high performers quartiles. The distributions are significantly different between the scenarios except for the variables ‘predominant gauge' and 'number of operational days per year' for the high performers, whose basic hypothesis (same distribution) was not rejected. The results of the Willcox Test, the difference between the medians, follow the results found in the K-S test except with the significance of the 'predominant gauge' for the high performers.

The proportion test (prop test) compared the proportion of existing railway sections between the low and high performance scenarios according to the low and high performers quartiles. It suggests that there is a significant difference between the scenarios, but mostly with the low performers. Considering the railway sections part of quartile 10, the basic hypothesis (same proportion) was not rejected for two concessionaires (FTL-TLSA, MO), the Mid-West region (MW), and all the technologies tested (transportation of hazardous material, embedded equipment, and CCO). As for the quartile 90, the basic hypothesis was not rejected for five concessionaires (EFC, FNSTN, FTC, MN, and MO), the North and Mid-West regions (N and MW), the CCO technology, and the restrictive regulation. Table 6 presents the results.

Table 4.5:
Statistical tests between the low and high performance scenarios.

TOPSIS model variables	Description	low performers (10th percentile) (n=735)		ks.test (p-value) (H_0 same distrib)	willcox.test p-value (H_0 same medians)	high performers (90th percentile) (n=735)		ks.test (p-value) (H_0 same distrib)	willcox.test p-value (H_0 same medians)
		low perf scenario	high perf scenario			low perf scenario	high perf scenario		
TOPSIS positive criteria (median)	predominant gauge	1.000	1.000	**0.000**	**0.000**	1.600	1.600	0.058	**0.004**
	min curve radius	143.000	143.000	**0.000**	**0.000**	254.000	600.000	**0.000**	**0.000**
	operational days/year	365.000	365.000	**0.000**	**0.000**	365.000	365.000	0.989	0.326
	installed capacity	5.800	13.400	**0.000**	**0.000**	52.500	12.620	**0.000**	**0.000**
	linked capacity	0.200	5.800	**0.000**	**0.000**	38.700	10.000	**0.000**	**0.000**
	bottleneck	3.840	50.150	**0.000**	**0.000**	73.270	86.630	**0.000**	**0.000**
	linked capacity*length	1.600	66.300	**0.000**	**0.000**	287.840	148.800	**0.000**	**0.000**
TOPSIS negative criteria (median)	increasing ramp tax	1.700	1.000	**0.000**	**0.000**	0.700	0.600	**0.000**	**0.039**
	auxiliary power	0.000	3,600.000	**0.000**	**0.000**	0.000	0.000	**0.000**	**0.000**
	idleness	5.400	6.460	**0.000**	**0.003**	11.200	1.990	**0.000**	**0.000**
	idleness percentage	96.160	49.850	**0.000**	**0.000**	26.730	13.370	**0.000**	**0.000**

Tobit model variables	Description	Yes	no	yes	No	prop.test (p-value) (H_0 same prop)	yes	no	yes	no	prop.test (p-value) (H_0 same prop)
railway operator	EFC	0	735	10	725	**0.004**	39	696	31	704	0.391
	EFPO	0	735	0	735	na	0	735	0	735	na
	EFVM	3	732	18	717	**0.002**	168	567	60	675	**0.000**
	FCA	247	488	132	603	**0.000**	17	718	116	619	**0.000**
	FNSTC	0	735	0	735	na	0	735	0	735	na
	FNSTN	0	735	0	735	na	6	729	7	728	1.000
	FTC	10	725	0	735	**0.004**	1	734	0	735	1.000
	FTL_TLSA	97	638	104	631	0.649	0	735	6	729	**0.041**

Table 4.5: Continued.

Tobit model variables	Description	Yes	no	yes	No	prop.test (p-value) (H_0 same prop)	yes	no	yes	no	prop.test (p-value) (H_0 same prop)
railway operator	MN	0	735	9	726	**0.007**	75	660	70	665	0.726
	MO	57	678	76	659	0.102	0	735	4	731	0.133
	MP	12	723	101	634	**0.000**	45	690	144	591	**0.000**
	MRS	5	730	183	552	**0.000**	365	370	227	508	**0.000**
	MS	304	431	102	633	**0.000**	19	716	70	665	**0.000**
location (region)	MW	60	675	47	688	0.228	75	660	74	661	1.000
	N	0	735	10	725	**0.004**	45	690	38	697	0.498
	NE	144	591	104	631	**0.006**	0	735	6	729	**0.041**
	SE	217	518	472	263	**0.000**	595	140	547	188	**0.003**
	S	314	421	102	633	**0.000**	20	715	70	665	**0.000**
diverse characteristics of the railway operation	hazardous cargo	659	76	661	74	0.931	588	147	662	73	**0.000**
	embedded equipment	730	5	726	9	0.420	728	7	696	39	**0.000**
	CCO	686	49	700	35	0.144	726	9	721	14	0.401
cargo type	agricultural	504	231	257	478	**0.000**	122	613	268	467	**0.000**
	general cargo	213	522	284	451	**0.000**	53	682	205	530	**0.000**
	Mineral	18	717	194	541	**0.000**	560	175	262	473	**0.000**
regulation type	restricted	49	686	216	519	**0.000**	138	597	139	596	1.000

MW = Mid-West; N = North, NE = Northeast; SE = Southeast; S = South.

4.4.7 Public and Management Policies

Evidences for public and management policies were obtained in two ways. First, from the significance of variables selected in the railway sections scores from each performance scenario. These results suggest that, in view of the common objective of increased efficiency, the regulator authority should pursue a competitive regulatory structure by removing restrictions or barriers to enter and exit and encourage sharing the railway section among operators. In the high performance scenario, concessionaires transport any kind of cargo and have a homogeneous operating performance, reducing the differences among the operators that is observed today (evidence of the low and medium performance scenarios). The use of technology of CCO for increasing the railway operation safety also contributes to high performance.

The second set of evidences is the availability for identifying the efficiency of the railway sections of each concessionaire. They can be classified in an ascending/descending order according to the score in each scenario and identify which sections are part of quartile 10 (low performers) and quartile 90 (high performers), facilitating the managerial actions for improvement. This is useful for both managing the railway track as well as for the regulating and inspecting bodies. It highlights what each operator should emphasize or reference to increase efficiency. Greater homogeneity on the network should be pursued. Tables 4.6 and 4.7 in the supplement present a list of high (low) performing railway sections of each concessionaire in the high (low) performance scenario, indicating length, region, idleness, predominant type of cargo, and TOPSIS score.

4.5 CONCLUSIONS

This paper analyses the efficiency of BRCS's railway sections in the period 2013-2016 using a hybrid method and the significance of the variables selected in the optimized scenarios. The hybrid methodology used applied a differential evolution genetic algorithm to obtain the weights of the variables selected in the TOPSIS model, building optimized extreme scenarios. The methodology proposed differs from studies already done in the literature with the application of hybrid models with a genetic algorithm for a multi-objective optimization and TOPSIS to rank the optimal solutions.

The database of railway sections made it possible to link performance to physical and operational characteristics, transportation capacity, idleness, and type of regulation of the sections of each concessionaire, allowing findings that contribute significantly to answering the research question.

The contributions of this paper are twofold. As to the best of our knowledge, a simulation of the extreme scenarios in a (railway) system based on the characteristics of its network subparts (the rail sections) using a genetic algorithm to optimize the performance of the entire system according to the TOPSIS scores of the subparts is an innovative contribution of the research. The methodology proposed can be applied to different economic sectors treated as a network such as passenger and cargo railway systems and energy or telecommunication transmission lines.

In the second stage, the significant determinants to achieve high performance of BRCS were revealed. In the high performance scenario, the performance of the concessionaires is more homogeneous, different from the low and medium performance scenarios where there is dispersion in the operating performance. The transportation of general cargo is significant for the results, different from the low and medium performance scenarios whose transport is concentrated in bulk mineral and agricultural products for export. The market structure in a monopoly format is inefficient because it can inhibit the rise of new services that contribute to reducing the idleness of the assets. CCO technology is significant for high performance because it allows for a dense railway operation with trains coming from different regions and destinations operated by several concessionaire in an environment of greater integration and complementarity. The high performance scenario suggests a market structure where there is neither restriction of access to the railway track nor barriers to the entry and exit of new operators and services.

The implication of the paper is to determine new guidelines for BRCS's long-term strategic planning in order to increase the system's average performance. Public managers should push the companies toward transporting any type of cargo, service diversification, a centralized control of the operation, and sharing the railway track. Competition and diversification are key elements for high performance.

The secondary data from the railway sections was a limiting factor in the research. Obtaining data of total and linked capacity of BRCS's railroad segments with selected origin and destination may allow new findings and be the object of future research to expand the knowledge of Brazilian rail cargo system's efficiency frontier.

[1] The results presented were obtained with the R software version 3.3.4 available at cran (https://cran.r-project.org/).

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4.7 APPENDIX A

Table 4.6:
Top two railway sections per concessionaire, high performance scenario.

concessionaire	trackway name	lenght (km)	region	Idleness (trains/day)	idleness (%)	predominant cargo	Topsis score
MRS	Ramal_de_Mangaratiba	13.600	SE	0.20	0.51	3	0.97307
MRS	Ramal_de_Mangaratiba	8.280	SE	3.40	8.08	3	0.97181
FCA	Casa_Branca_-_Uberaba	13.173	SE	1.20	12.12	1	0.97060
FCA	Casa_Branca_-_Uberaba	13.173	SE	0.80	8.89	1	0.97019
EFC	Ponta_da_Madeira_-_Carajas	171.000	N	0.00	0.00	3	0.96885
EFC	Ponta_da_Madeira_-_Carajas	171.000	N	0.00	0.00	3	0.96879
MP	Canguera_-_Boa_Vista_Nova	11.200	SE	2.10	10.50	2	0.96637
MP	Canguera_-_Boa_Vista_Nova	11.200	SE	2.50	13.51	2	0.96603
EFVM	Ramal_Tubarao	12.411	SE	0.20	0.52	3	0.96428
EFVM	Porto_Velho_-_Itabira	53.872	SE	6.11	11.49	3	0.96414
MN	Marco_Inicial_-_Alto_Araguaia	50.743	MW	0.00	0.00	1	0.96400
MN	Marco_Inicial_-_Alto_Araguaia	43.698	MW	0.70	7.69	1	0.96395
MS	Cacequi_-_Bage	13.127	S	1.70	24.29	1	0.96389
MS	Cacequi_-_Bage	30.209	S	0.00	0.00	1	0.96365
MO	Bauru_-_Corumba	16.211	MW	3.38	51.84	2	0.96274
MO	Bauru_-_Corumba	16.211	MW	4.60	56.79	2	0.96231
FNSTN	Acailandia_-_Porto_Nacional	42.000	N	0.62	11.48	1	0.96256
FNSTN	Acailandia_-_Porto_Nacional	57.000	N	0.39	8.59	1	0.96221
FTL/TLSA	Tronco_Norte_Recife	38.384	NE	-2.00	-100.00	2	0.96183
FTL/TLSA	Tronco_Norte_Recife	38.384	NE	-2.00	-100.00	2	0.96183
EFPO	Guarapuava_-_Cascavel	25.922	S	2.18	42.08	1	0.95954
EFPO	Guarapuava_-_Cascavel	25.922	S	2.18	42.08	1	0.95954
FNSTC	Porto_Nacional_-_Ouro_Verde_de_Goias	57.200	MW	4.48	100.00	1	0.95715
FNSTC	Porto_Nacional_-_Ouro_Verde_de_Goias	57.200	MW	4.36	100.00	1	0.95715
FTC	Linha_Principal	1.822	S	2.00	20.00	3	0.95805
FTC	Linha_Principal	18.050	S	1.60	16.67	3	0.95697

predominant cargo: agricultural = 1; general = 2; mineral = 3; region: MW = Mid-West; N = North, NE = Northeast; SE = Southeast; S = South.

Table 4.7:
Two worst railway sections per concessionaire, low performance scenario.

concessionaire	trackway name	lenght (km)	region	idleness (trains/day)	idleness (%)	predominant cargo	Topsis score
FNSTC	Porto_Nacional_-_Ouro_Verde_de_Goias	48.417	MW	6.10	100.00	1	0.01121
FNSTC	Porto_Nacional_-_Ouro_Verde_de_Goias	48.417	MW	5.18	100.00	1	0.01125
EFPO	Guarapuava_-_Cascavel	25.358	S	3.76	55.62	1	0.01971
EFPO	Guarapuava_-_Cascavel	25.922	S	2.18	42.08	1	0.02010
FTL/TLSA	Tronco_Sao_Luis	39.705	NE	1.00	33.33	2	0.02020
FTL/TLSA	Tronco_Sao_Luis	39.705	NE	1.00	33.33	2	0.02020
MO	Bauru_-_Corumba	23.594	MW	3.10	47.69	2	0.02022
MO	Bauru_-_Corumba	28.47	MW	2.90	49.15	2	0.02110
FTC	Linha_Principal	16.29	S	4.16	34.21	3	0.03001
FTC	Linha_Principal	18.05	S	1.94	19.48	3	0.03304
FNSTN	Acailandia_-_Porto_Nacional	51	N	1.67	28.69	1	0.04693
FNSTN	Acailandia_-_Porto_Nacional	42	N	1.31	20.57	1	0.04717
FCA	Casa_Branca_-_Uberaba	34.549	SE	0.48	6.65	1	0.05159
FCA	Casa_Branca_-_Uberaba	34.549	SE	0.80	10.26	1	0.05344
MP	Evagenlista_de_Souza_-_Pereque	18.443	SE	1.60	9.64	1	0.06109
MP	Canguera_-_Evangenlista_de_Souza	15.409	SE	0.11	0.58	2	0.06369
MS	Uvaranas_-_Apucarana	35.995	S	2.30	22.33	1	0.06288
MS	Uvaranas_-_Apucarana	35.995	S	1.88	18.29	1	0.06594
MN	Marco_Inicial_-_Rondonopolis	48.07	MW	1.14	12.15	1	0.08591
MN	Marco_Inicial_-_Alto_Araguaia	50.743	MW	0.00	0.00	1	0.08694
MRS	Posto_km_64_-_452_(Linha_do_Centro)	14.69	SE	26.30	34.65	3	0.15919
MRS	Posto_km_64_-_452_(Linha_do_Centro)	14.661	SE	0.20	0.40	3	0.16118
EFVM	Porto_Velho_-_Itabira	56.592	SE	37.21	46.65	3	0.51746
EFVM	Porto_Velho_-_Itabira	56.592	SE	33.54	43.42	3	0.53140
EFC	Ponta_da_Madeira_-_Carajas	171	N	2.88	11.92	3	0.77857
EFC	Ponta_da_Madeira_-_Carajas	174	N	2.85	11.89	3	0.78575

predominant cargo: agricultural = 1; general = 2; mineral = 3; region: MW = Mid-West; N = North, NE = Northeast; SE = Southeast; S = South.

5. CONCLUSION

The joint analysis of the findings of the papers that are part of this thesis makes it possible to draw a serie of conclusions that are of the interest to the federal government, which is responsible for planning the SFBC, the agency that monitors, regulates, and inspects the system, and also the administrators of the railways. The conclusions and insights that answer the research questions presented in the introduction are subdivided into three approaches: efficiency of the current model; recommendations for high-performance; and recommendations regarding the efficiency evaluation methodology. At the end, the limitations faced and suggestions for further research are discussed.

5.1 EFFICIENCY OF THE CURRENT MODEL

In the first paper, considering the sample data for the period 2010-2014, it can be concluded based on findings that the average efficiency of the SFBC is low, and the performance of concessionaires is heterogeneous, presenting a high dispersion. The concessionaire at the efficiency frontier (EFC) is an outlier. There are companies with growing yields and decreasing in scale that suggest different strategies for increasing efficiency, including: expanding the activities for those concessionaires with efficiency above the average efficiency and increasing returns to scale; or reducing the use of inputs (resources), such as rolling stock, or best inputs combinations, for those concessionaires with decreasing returns to scale. Concessionaires whose efficiency are under the average efficiency may adopt better operational practices, improve railway infrastructure, and expand or reduce inputs depending whether with growing yields or decreasing returns to scale. The type of gauge (wide) and the type of cargo transported (mineral and agricultural bulk) are significant for the efficiency scores. The shared use of the railway track, however, was not significant for the performance of the operators. Even though some railways have shared use, allowing the passage of trains from more than one concessionaire according to existing regulations, the volume of transport produced in the competitive structure does not differ from the structure under a monopoly.

The findings suggest that the Brazilian cargo railway system is designed for transporting a restricted profile of goods, and as a result a restricted number of clients, in isolated subsystems, intended for export, presenting low integration between rail operations and a low diversity of scope. This performance suggests to explain the low participation of rail mode in the freight transport matrix in Brazil (15%). The transportation of general cargo, the main demand of transport in Brazil (54%) (EPL, 2016), is marginally done by rail (1%) due to the existing difficulties in the network, such as winding and excessive length pathways, and/or shortage of supply or demand, and/or a lower managerial interest. This transportation is under the responsibility of the highway transport (87%), complemented by the waterway transportation (12%). The concessionaires of the SFBC pursue a more concentrated operation in solid bulk (95%) where the rail transport has a natural competitive advantage in costs, fuel consumption, and emission of GHG compared to highway transportation.

In the second paper, based on the sample object of meta-analysis of 21 studies selected in the literature, compiled in the period 2000-2016, some findings were decisive to explain the behavior of the average efficiency in various systems in different regions of the globe. The research suggests that the railway productivity and the average transport distance of freight (ATDF) are significant variables for increasing efficiency. They significantly determine conditions that push the rail systems in Japan and the US to increasing efficiency. The railways with passenger transportation services or mixed transportation services (passengers and freight) are significantly more efficient than systems for cargo only. This can be explained because the rail systems that transport passengers incorporate systems and operational procedures of signaling, control, and security that are more sophisticated than the railway systems exclusively for cargo, offering better conditions for increasing efficiency. These are the cases of more productive railway systems in China and in some countries of Europe, especially in France and Germany. The ability of the railway to combine transporting passengers and cargo simultaneously means better allocation of available resources and a potential gain in efficiency. This suggests an important warning mainly for the American and Brazilian rail systems where there is a predominance or almost exclusive cargo transport. In addition, the concessionaires EFC (benchmarking) and EFVM, among the most efficient in Brazil, operate with mixing the transportation of passengers and freight on the network granted. In other subsystems, the current concessionaires do not share the rail assets granted with other services, such as intercity or regional passenger services, even though there is a high average idleness in the great majority of railway sections. This issue is not on the agenda of the railway sector in Brazil, whether by the private operators side or in the planning of the federal government, demonstrating certain economic irrelevance that contradicts the findings. It would be necessary to deepen the knowledge about which passenger railway links may significantly influence the efficiency of the railway system in Brazil, reducing its idleness, which is not the object of this research. The variables of railway productivity and ATDF may help to clarify the issue.

In the third paper, analyzing the sample of railway sections of the SFBC in the period 2013-2016, the simulation of optimized scenarios brought additional findings to the previous researches. In a high performance scenario, the performance of the concessionaires is homogeneous, different from the low performance scenario where there is wide dispersion in the operating performance. The system carries all types of cargo because they are significant for high performance. The transportation of general cargo is significant for the efficiency of the sections, unlike scenarios of low and medium performance whose transportation of solid bulk cargo for export influences the scores. The structure in a monopoly for using the railway tracks is inefficient. The shared use of the railway is significant for high performance, avoiding the situations of a restriction of railway supply that can inhibit the emergence of new services that contribute to reducing the idleness of the assets. In this context, the CCO technology is significant for high performance since it allows controlling a railway's operation that is more dense, with trains coming from different regions, operated by several operators, offering differentiated services to customers in an environment of greater integration and complementarity. Sharing the railway tracks avoids typical situations of monopoly structures that may cause either a railway sub-offer or setting the transport prices above the operating costs by the current concessionaires. The high performance scenario suggests a market structure where there is neither restriction of access to the railway track, nor barriers to enter and exit of new operators and services.

The findings of the significance tests performed in the first paper and the characteristics of the optimized scenarios in the third paper suggest that the current SFBC fits in the medium performance scenario where concessionaires still have a heterogeneous performance, the transport is concentrated on a restricted profile of cargo and it is significant for the results, and the shared use of the track does not differ from the situation in a monopoly.

In order to increase the average efficiency of the system, new guidelines should orient the long-term strategic planning of the Brazilian railway sector so as to move the least efficient operators toward high performance, approaching them to the efficiency frontier. The regulatory reforms and the contractual structure should be a result from this strategic planning that defines the long-term targets for the entire system.

5.2 RECOMMENDATIONS FOR HIGH PERFORMANCE

The planning of the Brazilian rail cargo system should push it to the scenario of high performance through regulations, a competitive environment, and contracts. Based on findings, four strategic guidelines can be formulated. The ***first strategic guideline*** for high performance is that the system should be planned as an integrated network, correcting its initial distortion where railroads were installed in a scattered and isolated way, with winding and excessive length pathway (MUNHOZ, [s.d.]), to meet the export market almost exclusively. Even after the privatization process taking place in the 90s, when the SFBC was subdivided into subsystems inspired in the organization by RFFSA superintendences, the public role of the Brazilian railway network in the logistics of the country was not made explicit. Only production and safety targets were stablished as targets to each concessionaire. The business planning of the concessionaires is confined to the network granted. Besides, the governmental systemic planning is still highly linked to the construction of new isolated railways (BRAZIL, [s.d.]).

SFBC lacks an incentive for physical and economic integration of the rail lines that turns feasible the rail transport as part of an integrated logistic system for the internal distribution of goods in Brazil. The railway system should provide an economic response to the difficulties and obstacles of Brazilian logistics. The performance of the concessionaires will be significant for attaining this objective. The public planning should outline the targets and become co-responsible for the results to be achieved by the whole set of (private) operations on the integrated network, maximizing its economic effect. A physically and economically integrated network would allow the railroad to prepare itself for transporting general cargo and other services, expanding the economies of scope.

The ***second strategic guideline*** for high performance is the impetus for transporting any type of cargo and toward intermodalism. The aim is to transport all types cargo in order to reduce the average idleness of the system and to encourage the administration of the railways toward an intermodal logistics operation. Establishing specific contractual targets that drive the transportation of general cargo by the current concessionaires, whether directly or through partnerships with newcomers, would be significant to increase efficiency. It will require the railway companies to design a specific administration focused on transporting goods of a higher added value and toward multimodal operations. The physical and economic integration of railways previously highlighted could enable the trains to circulate on routes of internal distribution, being competitive with the highway transportation and meeting the needs of distribution logistics, going beyond the export routes to the ports, a characteristic of the rail transport in Brazil since the end of the 19th century. This will encourage intermodalism and the reduction of transportation costs, while requiring rules for interoperability, including standardizing the technical specifications for the control and safety of trains so that the compositions from different tracks can move freely along the network of the same gauge. To encourage the concessionaires to operate in the direction of transporting general cargo and intermodalism will increase SFBC's efficiency.

The ***third strategic guideline*** for high performance is a more efficient use of the assets granted, such as the railway track and the rolling stock. The suggestion is to make contractual mechanisms that aim to reduce the idleness and increasing the productivity of the rail track, the speed of the trains, and the use up-to-date and more efficient designs for the rolling stock, replacing the obsolete equipments that compromises the efficiency scores.

Finally, the ***fourth strategic guideline*** for high performance refers to the market structure. The findings indicate that using the railway track in the monopoly structure reduces efficiency. The regulations should pursue the shared use of the railway sections and promoting the diversification of services and economies of scope. Regional services feeding the trunk lines, connecting granted subsystems, and new direct connections should be encouraged by regulation, such as the short lines railways in the US market. The sharing of the less idle sections, the most critical ones for the current concessionaires, and the policies to encourage competition by the entry of new providers would be significant for efficiency. The scenario of high performance is similar to the models put into practice in the European Community based of Directive 91/440/EEC (EUROPEAN COMMUNITIES, 1991) and in the US, based on the theory of contestable markets (BAUMOL; PANZAR; WILLIG, 1982) and on the Staggers Rail Act (US, 1980). The removal of barriers to the entry and exit from the market (passengers and cargo), the use of competitive processes in approving operators, the guarantee of no discretions in the tariff, the competitive allocation of slots, and the clarification of the relationship between state (grant) and concessionaires (revenue) in the transportation of passengers are the main guidelines of these models.

These ***four strategic guidelines*** for achieving high performance in the Brazilian rail system should emerge from the strategic planning of the federal government, accompanied with targets and timelines to guide the business planning of the private sector granted subsystems. Without a well-defined strategy, the moving from a medium performance scenario to a high performance scenario will be mostly compromised.

In Brazil, however, the regulatory and contractual reforms as laid down in Law No. 13,448 (BRAZIL, [s.d.]) are being carried out without long-term systemic targets being set in place. The main concessionaires have a regulatory incentive and want to extend the term of their current concession contracts that are linked to the increase of the outputs without significantly modifying the market structure of the current model, privileging investments to expand the scale instead of scope. The absence of previous definitions from the public administrator and a regulatory stimulus especially regarding the diversification of cargo and services, the incentive to competition, and sharing the railway track which are significant for increasing efficiency, brings the risk therefore of the high performance scenario not being achieved, and, thus, perpetuating the characteristics of the current medium performance scenario. Based on the findings, the proposal of an early extension of the concession contracts in the rail sector as provided for in Law No. 13,448 does not show itself to be able to push the SBFC toward high performance.

5.3 RECOMMENDATIONS REGARDING THE EFFICIENCY EVALUATION METHODOLOGY

The agencies that monitor, regulate, and inspect the public services, such as the railway's operation in Brazil, may use methods for assessing the relative efficiency of the service providers and for establishing efficiency ranking. The submission of annual efficiency reports based on methods widely accepted in the literature, such as DEA, are desirable to boost the operators to increase efficiency and to identify the benchmarking

DMUs that will become the operational references for the others. The knowledge of more efficient operations in the Brazilian rail system based on scientific methodologies would facilitate, for an example, the public manager decision-making as to the appropriateness of early extensions of existing concessions on the basis of Law No. 13,448.

Some precautions must be taken into account. The findings suggest that the number of variables used in the model of evaluating the efficiency frontier of the operators can significantly influence the results. The increase in the number of variables may also impose greater rigidity and complexity to the evaluation model, making it inadequate for its purpose. The variables should be selected with parsimony, selecting those that are widely applied in the sector. The results found also indicated that the parametric models are statistically different from non-parametric models. In some cases, they can lead to higher scores than the non-parametric models. This can be explained by the sensitivity of non-parametric models such as DEA to the increase in the number of variables (COOPER; SEIFORD; TONE, 2006), the heterogeneity in the data from the DMUs, and the presence of outliers (KHEZRIMOTLAGH, 2013). In these cases, there may also be a loss of discriminatory power or a sudden fall in the DEA scores. The existence of a random error in the parametric estimates from measuring data (BOGETOFT; OTTO, 2011), statistical error, or other non-systematic influences (AMORNKITVIKAI; HARVIE, 2010) may also justify the statistical difference found, since the difference between the observations of combinations of inputs and outputs and the efficiency frontier in non-parametric and deterministic models such as DEA is fully attributed to inefficiency. The deterministic approach tends to overestimate inefficiency. In these cases, the use of the DEA methodology can be complemented by other valuation techniques, including parametric models.

5.4 LIMITATIONS AND SUGGESTIONS FOR FURTHER RESEARCH

This research had as a limitation the existence of data from secondary sources. Parsimony should be used when defining the strategy used for selecting articles for the meta-analysis because it can exert an influence in the results. The application of a meta-analysis in a productive sector requires, therefore, a considerable initial planning and may face constraints in estimating the variables initially selected, considering that part of the information may be omitted in some articles selected, demanding extra efforts from the researcher.

The study of the efficiency frontier of railway systems can be expanded by additional approaches. The influence of contextual variables and of regulatory and management mechanisms that can influence the market structure over the efficiency or the profitability of the companies can be investigated. Such as the significance of the existence of barriers to entry in the railways, discriminatory access in the allocation of slots to third parties, and the corporate ownership structure. The significance of regulatory conditions in different systems around the world that push the operators toward diversifying its cargo is another point of interest. The more diverse US market could be the object of research. The significance of regulatory conditions that allow the diversification of services with the harmony between cargo, mixed and passenger operations is another source of interest. The European and Asian markets of a mixed rail use could be the object of research. Finally, the significance of regulatory conditions that guarantee the interoperability of the railway tracks needed to promote competition is another focus of interest. The US and European markets, open to competition, may be the object of research. All of them can bring important contributions to the advancement in efficiency frontier in the railway sector.

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5.6 RESULTING PAPERS

This section summarizes the resulting papers that have been presented in conferences proceedings or published in journals.

MARCHETTI, D.; WANKE, P. Brazilian Railways: An Efficiency Analysis of the Operations Using DEA in Two Stages. POMS 27th Annual Conference. Orlando, 2016.

________________; _____________. Railways meta-analysis: a literature systematic review of the mean efficiency of the systems. POMS 28th Annual Conference. Seattle, 2017.

________________; _____________. Efficiency of the rail sections in Brazilian railway system, using Topsis and a Genetic Algorithim to analyse scenarios. POMS 29th Annual Conference. Houston, 2018.

________________; _____________. Brazil's rail freight transport: Efficiency analysis using two-stage DEA and cluster-driven public policies. **Socio-Economic Planning Sciences**, v. 59, p. 26-42, 2017.

MARCHETTI, D.; WANKE, P. F. Efficiency in rail transport: Evaluation of the main drivers through meta-analysis with resampling. **Transportation Research Part A: Policy and Practice**, v. 120, p. 83–100, 2019.